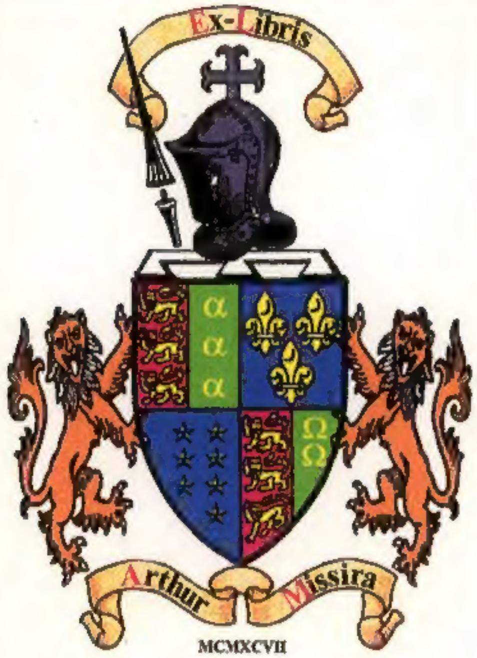
AIRCRAFT ELECTRICAL PRACTICE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AIRCRAFT ELECTRICAL PRACTICE

BY

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CHAPTER 1

Introduction

A BRIEF HISTORY OF ELECTRICITY IN AIRCRAFT

"It was therefore clearly demonstrated to all unbelievers that the dirigible balloon was now within the range of practicable possibilities." Thus comments Hildebrandt in his book *Airships Past and Present* on a flight made in 1884 by Renard and Krebs in their balloon "La France". The flight was significant because the balloon was successfully returned to its starting point by the use of a motor-driven propeller, but incidentally placed on record one of the earliest applications of electrical engineering in the air; for the motor which developed 8·5 horse-power at a speed of 50 r.p.m. was electric, deriving its power from accumulators. Its greatest disadvantage was its weight and the weight of its accumulators, but it was then the only kind of motor which was free from fire risk. Almost 20 years elapsed before a safe internal-combustion engine of suitable weight was developed to take its place.

Although electric motors were not light enough to be practicable as a means of propulsion, the use of auxiliary electrical equipment in balloons is recorded from the earliest times. In 1904 the "Lebaudy" was fitted with a small engine-driven d.c. generator for lighting, and an electrically operated camera. In 1918 the British Rigid 23 Class airships, having a weight of 52,500 pounds carried 801 pounds of electrical equipment. This included a 100-watt landing lamp, radio equipment, intercommunication telephones and an engine-room telegraph.

Some aircraft of this time were carrying wind-driven generators, mostly designed to provide power for radio transmitters, but general-purpose electrical systems were not introduced until the mid-1920's. These were initially 6- or 12-volt d.c. systems modelled very much on automobile systems. R. H. Woodall in the discussion to Ref. 1 (p. 312) stated that in 1936 two 24-volt 1-kW. d.c. generators were installed as a paralleled generator system in Short "C" class flying boats and that this was the first British paralleled system; 24-volt generators were then just coming into use and became general early in the second world war.

From about this time aircraft electrical systems were sufficiently developed to make electrical actuation of such things as flaps and undercarriages a practicable possibility, and aircraft designers were faced with a decision between the choice of electrical and other methods of actuation. Most designers preferred hydraulic or pneumatic methods because they were well proven, but a few aircraft emerged which were termed "all-electric" aircraft. Notable examples are the British Stirling bomber and the German Focke-Wulf. All-electric American designs appeared fairly early in the second world war, the best known being the Boeing Flying Fortress and the Super Fortress. These aircraft, remarkable for size and heavy defensive armament, also represented a high degree of development of the 24-volt d.c. system. The "Superforts" employed six 9 kW. generators which provided power for all the usual services and also for controlling, co-ordinating and manoeuvring five-gun turrets.

These early electric aircraft, if not in every case highly successful, provided experience from which post-war development was directed. Despite the many setbacks which electrical installations had experienced, post-war designers were almost unanimous in accepting relatively large electrical systems, and aircraft electrical engineering became recognizable to electrical engineers as a new branch of their profession, and to aircraft engineers as yet another subject which demanded the services of specialists. It is to be expected that there were compelling technical reasons for this trend and some of these may be revealed by considering the things which are now being done electrically.

APPLICATIONS OF ELECTRICITY IN AIRCRAFT

Aircraft, like other forms of transport, are constructed and employed for a multitude of different purposes. Each application, if it is to be economic and satisfactory, requires individual consideration in almost every respect. Airframes must be of proportions and strength appropriate to the load and performance, and engines must have output and specific consumption matched to give the performance economically. Similarly, the electrical system requires fundamental consideration and study to determine the type and capacity of the system, the kind of generators and generator drives and the principal things which are to be done electrically, and decisions are necessary early in the planning of a new aircraft.

It is consistent with the early distrust of electrical equipment that in early aircraft the only things done electrically were those which could not be done in any other way. Although not part of the main electrical system, the ignition systems of the main engines are an example of electrical equipment which was accepted and developed to a high degree because there was no other practicable method. Since then the development of electronics has

made available many different types of equipment to assist in navigating, flying and landing aircraft and these are universally accepted as indispensable. Similarly, in the fields of radio communication and lighting, electricity has no rivals. The adoption of electrical methods for other things, particularly those which do not require appreciable power or which require power only for limited periods of time, is possible with very little development of the electrical system already provided for the essentials. Thus, the increase in the types of equipment which are by nature electrical, has fostered the use of equipment for which alternatives are available.

Electrical actuators are one such type of equipment, now widely used for the operation of fuel cocks, flaps and other similar parts which require only intermittent drives. They have also been adopted by some designers for heavier operations such as undercarriage actuation, bomb-bay door operation, dive-brake actuation and tail-plane incidence adjustment. Closely associated with many of these is a system of indication, warnings and interlocks. Electrical methods provide several alternative kinds of indication, notably, lamps, indicators, meters and audible warnings, all of which are readily co-ordinated with the main equipment.

Electric starter motors have been used for all sizes of piston engines and for most turbines, but owing to the longer starting cycle and high power required for turbines, alternative means of starting have been introduced for some military aircraft.

Electro-hydraulic systems of actuation are extensively used for propeller pitch control and powered flying controls. Here the electrical system provides power to drive a hydraulic pump which in turn powers hydraulic actuators. This system eliminates the need for precise switching or control of the electric motors, and is particularly suited for operations requiring very high forces for short periods of time. As with electric actuation systems, electrical indication and control circuits are invariably used.

Electrical de-icing of propellers, engine intakes and parts of the airframe demands relatively large powers, but with the important concession that de-icing heaters do not require close control of either voltage or frequency. To minimize the power required it is usual to heat various parts successively by using a cycling switch driven by an electric motor.

Instrumentation, the measurement of such quantities as pressure, temperature and positions of controls, can be done without electricity but electrical methods are now generally preferred. The power required is small, and the advantage of remote presentation of the measured quantity with nothing more cumbersome than interconnecting cables, is usually a deciding factor. Electrical instruments have the further advantage that they are able to provide information in the form of electrical signals which are generally suitable for automatic controls such as air conditioners and auto-pilots.

Control of cabin pressure, humidity and temperature call on electrical services principally for the operation of valves, fans, temperature sensing devices and control equipment. A little local cabin heating is done electrically, but most of the heat is derived either from the engines or from fuel-burning heaters. Refrigeration in civil aircraft is normally operated only on the ground and sometimes for a short time after take-off. It may represent a load of up to 10 kW. Refrigeration systems for very-high-speed aircraft, the skins of which become heated by friction with the air, may in the future demand additional electric power.

Military aircraft carry special types of radar equipment for such purposes as ground scanning, forward and rear warning of approaching aircraft, submarine locating and long range early warning. Radar beam guidance for some kinds of guided missiles may also be required. Power supplies for missiles are sometimes of non-standard voltages and frequencies and may be required to be available from the aircraft power system. Bombing equipment, such as computers, aiming equipment, arming and release equipment are nearly always electrical. Similarly, gun-turret drives, aiming and firing mechanisms have all been extensively electrified.

Catering equipment for cooking and heating meals, and water heaters for kitchen and toilet use, require substantial power but are non-essential loads which can be shed in the event of generator failure. New equipments which require electrical power are still being introduced and most predictions indicate that future aircraft will require substantially greater electrical power.

CHAPTER 2

Special Requirements of Aircraft Equipment

THE payload of most civil aircraft is about one-fifth of the all-up weight, that is, the weight when fully loaded and ready for flight. The figure for high-performance aircraft is only about one-tenth, a very small proportion when compared with other forms of transport. Fuel for an aircraft will account for up to two-fifths of its all-up weight, depending very much on the range of the aircraft. From these facts it is evident that errors in design leading to an increase in the all-up weight of about one-tenth could result in an aircraft with practically no payload capacity, or with the intended payload capacity but only three-quarters of the intended range. The same errors in the course of motor-vehicle design would reduce the load-carrying capacity significantly but not nearly so drastically.

WEIGHT

It is therefore not surprising that aircraft designers are very critical about the weight of their aircraft and particularly about the weight of equipment which is of a secondary nature. Engines, airframes and surfaces giving lift and control, although subjected to severe weight scrutiny, are clearly fundamental to an aeroplane and the question of omitting them cannot arise. The same cannot be said, however, of much of the electrical equipment which is of a secondary nature; for example, that which provides services to assist in navigating or flying the aeroplane, or provides comfort services such as heating and air conditioning, or performs a function which might be performed in some other way. All such equipment is particularly exposed to criticism, and it is to be expected that its weight will be carefully watched.

When an aircraft is in an advanced stage of design or in service it is possible to express the penalty of increased weight fairly precisely, either as a reduction in operating range or as a loss of payload. Figures have been quoted for large civil aircraft of the money earned by each pound of payload capacity and these lie between £40 and £70 a year. Thus, if 100 lb. of equipment is removed from each of a fleet of 10 aircraft, and the aircraft operate

for 10 years, the total earnings are increased by between £400,000 and £700,000. Since the cost of fuel to carry one pound weight for a year is quite small, these earnings can be mostly profits.

Quite frequently the weight added to an aircraft by the addition of an item of equipment is considerably greater than the weight of the equipment itself. There may also be other penalties, and the assessment of the effective weight, that is, the actual weight together with the penalties, can be difficult and the methods used are often the subject of controversy. Considering a simple example, suppose that additional cabin lights are fitted and that the weight of the lights is 10 lb.; to this must be added the weight of cables from a junction box and the weight of any trunking, cable sleeving or strapping. Assuming that the existing switches can be utilized, and that the generators and cables to the junction box can carry the additional load, the direct weight increase can be readily assessed. A probable total is 11 lb.

There is, however, at least one indirect weight increase, the fuel consumed by the aircraft engines in order to provide increased power to the generators. If it is assumed that the lights have a consumption of 250 watts and that the efficiency of the generators and distribution is 70 per cent, then the additional power required is about ½ h.p. At a specific fuel consumption of 0·9 lb. per h.p. per hour this will incur a penalty of 2·7 lb. on a six-hour flight. Thus, provided additional fuel capacity is available, as should be the case if the aircraft is not operating at maximum range, this installation may be installed if the payload is reduced by 13·7 lb. Should the extra fuel capacity not be available, an additional penalty would be incurred by the increase in the size of the fuel tanks.

The effect of added weight has so far been considered in terms of reduced payload, which is probably the most useful way when considering an existing aircraft. In the design stage when aircraft payload, range and performance are specified, the addition of weight without detracting from the specification may be considered in terms of the increase in all-up weight. This increase is many times greater than the added equipment weight because additional weight requires a stronger structure, a larger wing area, larger engines, larger fuel tanks and so on. The ratio: Increase in all-up weight/Added equipment weight, is sometimes called the Weight Growth Factor or Aeroplane Growth Factor and lies between 5 and 10, the higher figure applying to very-high-speed aircraft and the lower figure to the more conventional civil aircraft.

A weight penalty incurred by most aircraft generators and by some other equipments is that arising from the supply of cooling air. It is common practice to obtain cooling air from a forward-facing scoop and, although it is known that such a scoop imposes a drag on the aircraft, the precise penalty is not easily evaluated. It may be expressed either in terms of the extra fuel to be carried to overcome the drag on a particular journey, or as reductions

in maximum speed and range. It is a significant penalty on most aircraft and a serious one on high-speed aircraft. Similarly difficult is the assessment of penalties arising from the supply of oil for cooling and of tapping air from the main engine compressors for air-turbine-driven generators.

Items of ancillary equipment are often of comparable weight with the electrical equipment itself. Examples are: fixing bolts, supporting brackets and ducting for cooling air and compressed air.

RELIABILITY

A reliable system or item of equipment is one which always does what is expected of it. Reliability should be distinguished from such qualities as length of life and ruggedness since, although desirable for many reasons, these qualities are not essential for reliability. Reliable service can always be obtained from short-lifed equipment provided it is replaced as often as is necessary; similarly, other shortcomings do not prevent reliability being obtained if they are understood and provision is made for them. Perfect reliability can never be attainable, but reliability can always be improved and it is for the aircraft designer to determine the degree of reliability to be accepted in any particular case. Reliability can be improved by attention to such things as: (*a*) design and construction; (*b*) installation; (*c*) mode of operation; (*d*) maintenance; (*e*) duplication of equipment.

Equipment designers can generally increase reliability by designing for low electrical and mechanical stresses and moderate temperature rises, and by avoiding unproven methods, materials and techniques, but such designs are inevitably heavy. Since the penalties for weight are severe, aircraft equipment cannot be designed for the utmost reliability, yet it must be adequately reliable. Here is a compromise which demands the highest design skill. Constructors can increase reliability by closer inspection and more extensive testing, but not without increasing production time and costs.

The method of installation of equipment can have an important effect on reliability. Ideally, all electrical equipment should be installed in an environment rather like that of a modern telephone exchange or power station. Practically, it must be capable of operating in the aircraft environment, because the cost, in terms of weight, of providing the ideal environment is impossibly high. Improvement in reliability is possible, however, by adhering to such principles as the minimizing of the number of electrical connexions or joints, particularly in the vicinity of the engines where vibration levels are high, and by avoiding cable runs which leave lengths free to move under vibration or suffer undue flexure in flight.

Reliability can usually be enhanced by underrunning the equipment, since this leads to the same conditions as are obtainable with conservative design. Owing to the weight penalty this is not generally an acceptable

practice in aircraft, except in the generating system. There, safety considerations require reserve generating capacity, and for several reasons it is desirable to have all generators operating simultaneously.

Maintenance is essential for reliability but must be minimized, owing to the cost and the time lost during which the aircraft is grounded. For military aircraft, the difficulty of effecting maintenance under operational conditions is such that frequent or extensive maintenance cannot generally be accepted as a means of obtaining adequate reliability. Duplication or triplication of equipment is a method of obtaining an installation which has a greater reliability than that of the individual sets of equipment. The direct penalties are cost, weight and maintenance. Indirectly, duplicated equipment carries a further economic penalty because the probability of failure increases with the number of equipments and the failure of any one item would be sufficient to delay a take-off.

The degree of reliability which is acceptable is determined by safety and economics. Present opinion in Britain is that a fair standard of safety in civil aircraft is being maintained if the number of accidents caused by electrical failures is not greater than one in every million flying hours. In an aircraft which depends on its electrical system for vital services and instruments this can only be achieved at present by very high standards of design, installation and maintenance, and some duplication, since failures for electrical machines such as generators, motors and actuators number between 0·1 and 1 per item every 1,000 flying hours. The direct economic consequences of unreliability arise from delayed take-offs, returns to base after take-off and unscheduled stops. The earning capacity of a large civil aircraft has been estimated at between £300 and £400 per hour. This and expenses arising from jettisoned fuel, additional landing fees and catering for passengers, make unreliability very costly. Present operators advocate an increase in reliability even at the expense of some increase in weight. In military aircraft the risk of accidents from unreliable equipment is small compared with the risks of operational flying, and the penalties of increased weight on performance and range may themselves increase the danger from enemy action.

LIFE

Aircraft equipment should, ideally, require no attention throughout the life of an aircraft. This cannot generally be achieved and the next best objective is to minimize the maintenance required and make it conform to the normal aircraft maintenance system. This is usually a system of graded checks to be carried out after increasing periods of flying time, the least comprehensive check being made after about 100 flying hours and requiring less than 24 hours, and the most comprehensive being made after 1,500 to 2,000 flying hours and requiring about 10 days. A fair target life between overhauls

of electrical equipment is the time allowed between these major checks. At present this is not generally met by rotating electrical machines, for which lives of as little as 750 hours are not uncommon.

Maintenance should be minimized because it is both costly and time-consuming. The complexity of modern aircraft is such that specialists are required to service each of the several systems and assemblies, such as electrical, electronic and hydraulic systems, airframes and engines. The compactness of equipment bays and assemblies is of such a degree that the removal of one part frequently necessitates disturbing another, and specialists of more than one kind are involved on one job. The small size of an aircraft also severely limits the number of men who can be employed simultaneously.

Unscheduled maintenance arising from unexpected failures is preferably dealt with by replacement of parts and assemblies, since the turn-round time is frequently scheduled as only 40 minutes. The installation of the less reliable equipment should therefore allow easy removal and ensure easy and correct replacement. A considerable amount of unscheduled work is necessarily done with the aircraft in the open, adding further to the difficulties of the work. Servicing in the air is impossible for much of the equipment which is inaccessible from the cabin, and it is impracticable as a normal procedure.

CHAPTER 3

Environment of Aircraft Equipment

THE most significant quantities which make up equipment environment are (*a*) atmospheric pressure, (*b*) temperature, (*c*) humidity (these are all climatic conditions) and (*d*) vibration, (*e*) shock, (*f*) acceleration (which are conditions brought about by the aircraft). Some adverse environments such as corrosive and dust-laden atmospheres are rarely experienced by aircraft equipment, but the range of climatic conditions is wider and the severity of acceleration and vibration greater than that experienced by almost any other electrical equipment. Coupled with the light weight and reliability requirements, these conditions pose design problems which, rather too often, result in equipment having a limited life or requiring excessive maintenance.

ATMOSPHERIC PRESSURE

A graph relating pressure and altitude is shown in Fig. 3.1 which is based on information published by the International Commission for Air Navigation (I.C.A.N.). Civil aircraft with pressurized cabins may fly at altitudes up to 45,000 feet and military aircraft still higher, thus experiencing atmospheric pressures of only 2 or 3 lb. per sq. in. Some electrical equipment can be accommodated in pressurized zones but, because of the extra structural weight, these zones are restricted in size to provide only for the crew and, in civil aircraft, for passengers and their baggage. Equipment must therefore often be designed for outside conditions. Certainly heat-

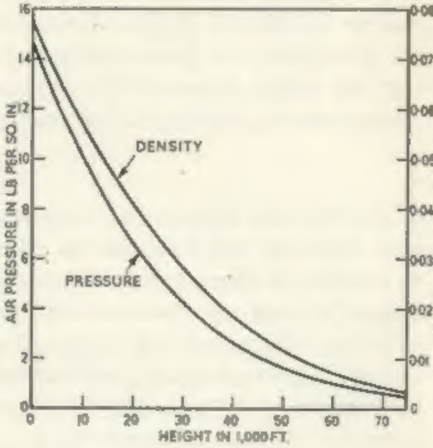
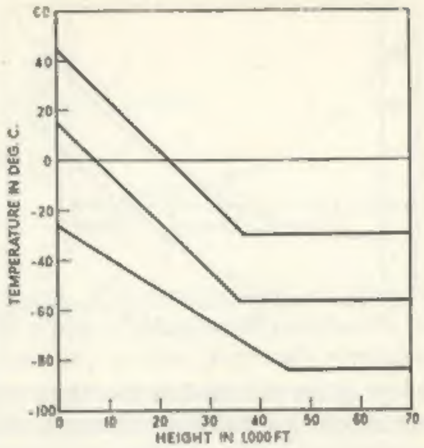


FIG. 3.1. *Curve relating air pressure, density and height above sea level.*

FIG. 3.2. *Curves relating air temperature and height above sea level.*



dissipating equipment—such as generators—must be outside if the use of heat exchangers or refrigeration systems is to be avoided. Operation at reduced pressure has several effects principally caused by: (*a*) the reduced breakdown voltage or dielectric strength of the atmosphere, and (*b*) the reduced transfer coefficient of heat from surfaces to the atmosphere.

Reduced breakdown voltage leads to more severe arcing at circuit-breaker contacts and commutators. Special provision is generally necessary in the design of circuit-breakers in order to minimize the duration of arcing, and spark-free or "black" commutation is difficult to achieve. The rupturing capacity of fuses may also be affected. Reduced heat transfer coefficient means that the cooling effect of air is reduced and that a greater volume of air must be used to obtain the same effect. This is one aspect of air cooling which may make it unsuitable for future aircraft.

Cycling through the pressure range of 2 to 15 lb. per sq. in. can cause moisture to accumulate in equipment which is imperfectly sealed, owing to "breathing". This probably results in the following sequence of events. Air is "inhaled" at sea level at moderate temperature and humidity; at altitude the air in the equipment is cooled below dew point and relatively dry air is "exhaled" leaving condensed water in the container. Equipment should therefore either be sealed well enough to prevent breathing, or be left open.

ATMOSPHERIC TEMPERATURE AND HUMIDITY

Graphs relating temperature and altitude are shown in Fig. 3.2. Whereas pressure is not greatly affected by the seasons or geographical position, temperature is so affected and extreme curves are shown in addition to the I.C.A.N. curve which represents the average atmosphere in temperate latitudes. In each case temperature ceases to change significantly above a certain height known as the tropopause. From these graphs it can be seen that all aircraft equipment should, ideally, be tested between about +50 and −80 deg. C. Tests at higher temperatures may be required for equipment which is operated in an artificially heated environment.

The steady fall in temperature from sea level to the tropopause is

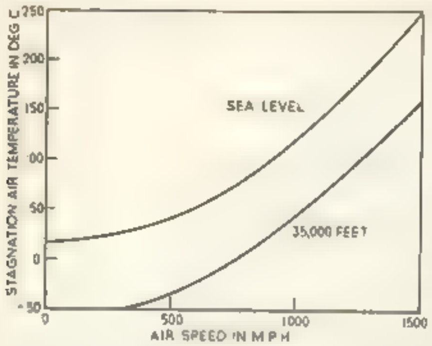


Fig. 3.3. *Approximate curves relating stagnation air temperature and air speed.*

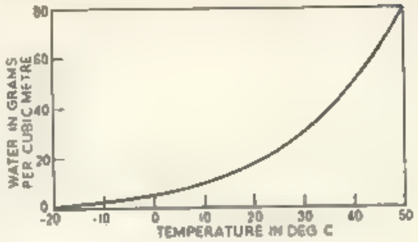
helpful in offsetting the reduced cooling effect previously mentioned. Extremely low temperatures have a number of undesirable effects such as (*a*) reduced accumulator performance; (*b*) increased lubricant viscosities; (*c*) decreased flexibility of insulating materials. One advantageous effect—the reduced resistivity of copper conductors—is unfortunately too small to offset the disadvantages (*a*) and (*b*). Although ground temperatures are not the lowest experienced, starting at low temperature is the condition in which the effects are most noticeable. In operation, some equipment, such as the accumulator, is self-heating and can fairly easily be maintained at satisfactory temperatures even in the lowest atmospheric temperatures.

The highest atmospheric temperatures occur at sea level but do not usually determine the upper operating temperatures of electrical equipment since most ground running is either at reduced power or of short duration. High temperatures adversely affect the life and stability of accumulators. Insulation resistances are lowered with temperature but, except in very critical circuits, this effect is not usually of practical consequence. Satisfactory operation over the complete temperature range is more difficult to achieve than operation at either extreme, and has required the development of special lubricants and insulating materials. Aircraft exposed to tropical sun receive radiated heat and experience skin temperatures in excess of the highest air temperatures. The internal temperature is also raised if air circulation is restricted. This condition is normally avoided, but may arise in aircraft which are not in use. The deteriorating effects of such temperatures on electrical equipment should be considered.

Air available for cooling purposes often has a temperature substantially higher than the ambient temperature. Air taken from the early stages of a turbine compressor is always at elevated temperature and, in high-speed aircraft, air collected by a scoop is adiabatically compressed. The temperature of such air, termed the stagnation temperature, is indicated in Fig. 3.3, and it can be seen that this is significantly higher than the ambient temperature at air speeds in excess of about 500 m.p.h. Adiabatic temperature rise will be an important factor limiting the rating of ram-air-cooled generators in very-high-speed aircraft.

The *humidity* of the atmosphere is expressed in different ways but the

Fig. 3.4. *Weight of water vapour held by saturated air over a temperature range.*



principal modes of expression are: relative humidity and absolute humidity. The latter is defined as the mass of water contained in unit volume of atmosphere and is often measured in grams per cubic metre. The measurement of absolute humidity, although not difficult, is not simple enough to be practicable for regular observations, so that relative humidity is more frequently measured. This is defined as the amount of water contained in a sample of air and is expressed as a percentage of the amount of water required to saturate the air. The amount of water required to saturate air, and therefore the value of relative humidity, depends very much on temperature, as shown in Fig. 3.4.

Extremely low absolute humidity occurs at altitudes in excess of about 20,000 ft., and this condition is the primary cause of extremely rapid wear of carbon brushes. Values are often less than 0·001 gram per cubic metre compared with about 10 grams per cubic metre at sea level.

High values of absolute humidity are not of much consequence provided the air temperature is also high, but high values of relative humidity and the occurrence of saturation is indirectly the cause of many troubles. It can be seen from Fig. 3.4 that if saturated air is cooled, less water can be contained as vapour and the excess must be condensed out. Condensation is likely to occur in places which are well protected from rain and in which full precautions against corrosion and electrical leakage have not been taken. It can occur when cool equipment is subjected to a warm atmosphere or when a closed volume of warm air is cooled. An interesting example is to be found in aircraft which cruise at fairly high altitudes in sub-zero temperatures. Interior parts of the cabin which are in good thermal contact with the skin may cool the local cabin air to saturation temperature, even though the relative cabin humidity is being maintained at only about 30 per cent for passenger comfort. Condensation on these parts is likely to appear as frost. On subsequent descent into warmer atmosphere, this melts and trickles down into the lower parts of the cabin, under the floor of which electrical equipment is often installed.

VIBRATION, SHOCK AND ACCELERATIONS

The principal sources of *vibration* are the main engines, propellers, and air-flow over the aircraft surfaces, the latter being influenced very much by

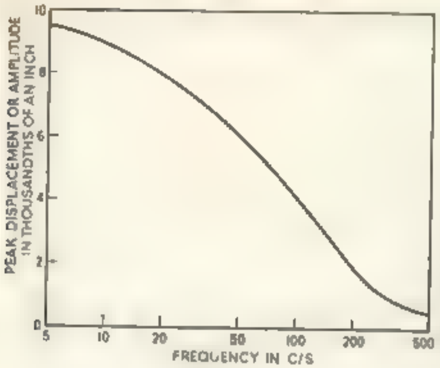


FIG. 3.5. *Amplitudes of vibration along the vertical axis in the central region of a typical aircraft.*

aircraft speed and to a lesser extent by propeller wash and jet efflux. Rotating machines, such as electrically driven pumps for powered flying controls, may also give rise to vibration but, generally, electrical equipment is not a serious source of vibration. The firing of guns may be a source of severe vibration occurring infrequently and only for restricted periods. The level and nature of vibration varies considerably throughout an aircraft structure, but before discussing this it may be helpful to define vibration and the terms used to describe it.

Vibration means continued movement of an oscillatory or repetitive character. Movement has direction, and it is usual to define three axes and to resolve vibration into components along these axes. In aircraft, three convenient axes are fore-and-aft, lateral and vertical, as indicated in Fig. 3.9. A precise resolution of vibration may show that it also has torsional components about one or more of these axes, but these components are generally of secondary consequence. At any one flight condition the nature of vibration along one of these axes is of irregular waveform which can be shown to contain sinusoidal components of many frequencies within a wide range. From the study of a number of flight vibration records it is possible to estimate the peak displacement or amplitude occurring at any frequency. This information, for a typical aircraft, is shown in Fig. 3.5. It may be seen that large amplitudes of movement or displacement occur at the lower frequencies, a fact which may be verified by observation in road vehicles. An alternative form of presentation is shown in Fig. 3.6 where the vibration level is expressed in terms of the maximum acceleration occurring during a cycle of vibration. Acceleration itself is expressed in terms of the acceleration caused by gravity, g. The relationship between amplitude and acceleration for a single vibration frequency may be determined by writing the expression for displacement in terms of time and differentiating twice.

$$\text{Displacement} = A \sin 2\pi ft \qquad (1)$$

where A is the peak value of displacement or the amplitude; f is the frequency in cycles per second (c/s); and t is time: $t=0$ when displacement$=0$. Differentiating once gives velocity of movement,

$$\text{Velocity} = A\, 2\pi f \cos 2\pi ft \qquad (2)$$

and differentiating again gives acceleration of the moving or vibrating part,

$$\text{Acceleration} = A(2\pi f)^2\,(-\sin 2\pi ft) \qquad (3)$$

Generally only the maximum value of acceleration is of interest, and this occurs when the term within the bracket ($-\sin 2\pi ft$) has its maximum value of unity. Thus the maximum or peak acceleration is equal to $A(2\pi f)^2$ in inches per second per second, if A is in inches. This may be expressed in terms of g by dividing by g, which has a value of 32·2 feet per second per second (ft/sec.^{2}) or 386 in./sec.^{2}. As an example Fig. 3.5 shows that at 100 cycles per second (c/s) the greatest amplitude of vibration expected is 0·004 in. The corresponding acceleration in terms of g is

$$\frac{0{\cdot}004 \times (2\pi 100)^2}{386} = 4{\cdot}1\ g.$$

This means that the highest acceleration experienced by the vibrating part during the vibration cycle is 4·1 times greater than the acceleration in free fall. It exists only instantaneously and, since the acceleration follows a sinusoidal law as shown by equation (3), it will pass through all values between maximum, zero, and maximum in the opposite direction.

The use of displacement and acceleration to describe vibration levels is convenient because both have practical significance. Displacements between vibrating and non-vibrating parts determine the amount of flexure experienced by cables connecting the two. Acceleration of a vibrating part gives a direct indication of the force experienced by the part and its supporting structure, since by Newton's Second Law, force$=$mass$\times$acceleration. For example, a part weighing 1 lb. accelerated at 10g is being acted on by a force of 10 lb. The supporting structure for the part is being stressed by a 10-lb. load instead of the normal load of 1 lb. Fig. 3.9 shows a likely subdivision of an aircraft into vibration zones and Figs. 3.6, 3.7 and 3.8 give typical vibration levels occurring in each zone.

Vibration isolators are used for some electronic equipments and control equipments, such as carbon-pile regulators and circuit-breakers. The characteristics of a simple isolator supporting a piece of equipment are represented

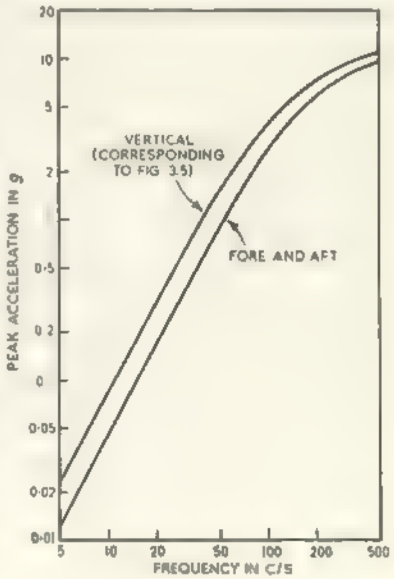


FIG. 3.6. *Peak acceleration, during vibration, in the central region.*

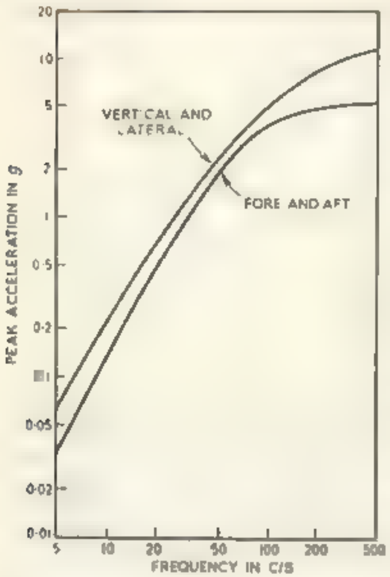


FIG. 3.7. *Peak acceleration occurring during vibration at the extremities of a typical aircraft.*

in Fig. 3.10. From this it can be seen that isolation is only obtained at frequencies substantially greater than the natural frequency of the isolator-load combination. At lower frequencies, and particularly at frequencies near the natural frequency, the amplitude of movement experienced by the isolated equipment is actually greater than would be experienced if the equipment were mounted directly on the vibrating structure. These large amplitudes determine the clearance necessary between the isolated equipment and fixed parts. Good isolation therefore requires a low natural frequency, but isolators having very low natural frequencies are not usually practicable because they also have large static deflections and allow large amplitudes of movement at low frequencies. The design of isolators to be equally effective in three axes and to be unaffected by large temperature changes are practical problems which are only partially solved. With the substitution of transistors in place of valves it is to be expected that future electronic equipment will be less sensitive to vibration and capable of satisfactory operation without isolation.

Vibration testing and proving has undergone considerable development in recent years but is not yet capable of very precise results. This is because it is difficult to measure vibration levels accurately and to generate vibration free from harmonic distortion. It is also difficult to apply vibration to a test piece without introducing vibration

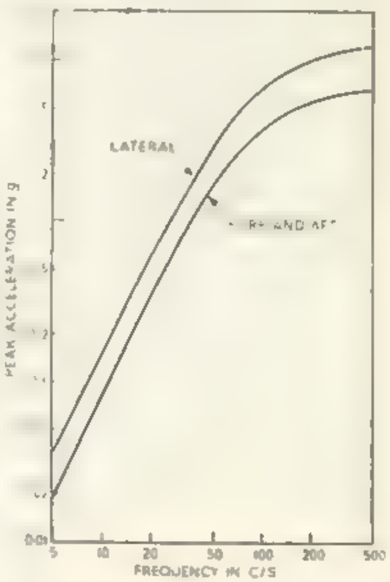
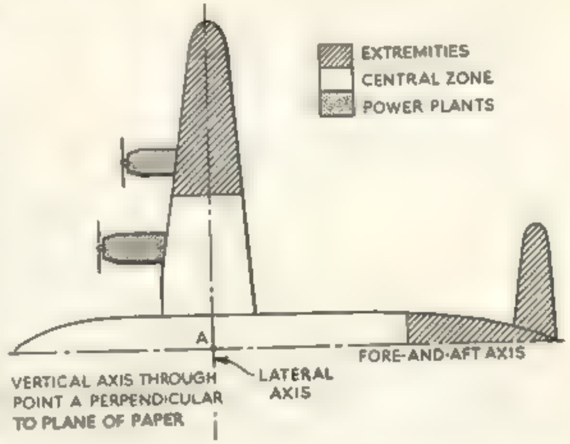


FIG. 3.8. *Peak acceleration occurring during vibration in the reciprocating power units.*

FIG. 3.9. *Vibration zones and axes.*



along or about more than one axis. The essential tools for vibration testing are a vibration generator and means of measuring the level and effects of vibration on the test piece. Vibration generators are usually linear rather than torsional and employ the principle of the moving-coil loudspeaker, but are constructed in heavier style in order to transmit the much larger forces generated.

Power for the generators is usually obtained from thermionic-valve oscillators and amplifiers, adjustment being provided both for amplitude and frequency. The level of vibration to which a test piece is subjected may be measured by an accelerometer on the mounting assembly, or by measuring the deflection of the mounting. The equipment under test may be checked in several ways. Mechanical resonances are generally audible and often visible if observed under a stroboscopic lamp flashing at approximately the resonant frequency. The effects of vibration on electrical performance may be determined by observing the electrical output on an oscilloscope, looking particularly for intermittent or distorted output.

A typical test procedure is to vibrate the test piece at the levels expected in flight, passing through the expected frequency range slowly enough to be able to locate resonances. Sustained vibration is then applied at the resonant frequencies in order to determine the consequences. Failure within a few minutes is not uncommon when severe mechanical resonances involve large deflections of such things as single-strand copper wire and soldered multi-strand wire. Finally, the vibration spectrum may

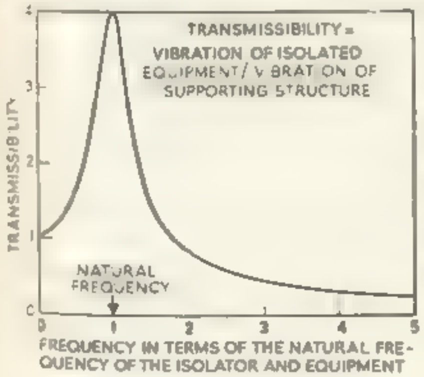


FIG. 3.10. *Characteristic of a simple vibration isolator.*

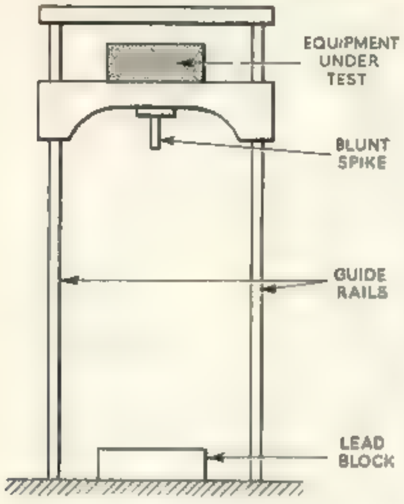


FIG. 3.11. *The basic features of a drop-test rig.*

be swept slowly and repeatedly. Tests are normally carried out successively in the three axes.

Shocks occur in aircraft operation principally on landing and as a result of bumpy or gusty air conditions. Carrier-borne aircraft may experience additional shocks from arrestor wires during landing, and from catapult mechanisms at take-off. During crash landings and ditchings shocks causing accelerations up to 25g are to be expected, and equipment mountings are designed to withstand these shocks. Shock testing is fairly easily effected by dropping the equipment and arresting the fall in a very short distance. Fig. 3.11 depicts a simple drop-testing rig in which the falling platform carrying the equipment under test is arrested by the penetration of a spike into a lead block. Assuming the retardation is uniform, the deceleration in g is equal to distance dropped÷depth of penetration.

Accelerations of relatively long duration, compared with those occurring during cycles of vibration or periods of shock, occur as a result of aircraft manoeuvres, propulsion and braking. Manoeuvres can cause accelerations as high as 13g in fighter aircraft and 7g in larger aircraft. Propulsion thrust is not normally capable of producing more than about $\frac{1}{2}g$ in level flight. Braking decelerations are also small, being limited by tyre adhesion and the retarding thrust available from reverse thrust devices.

Tests on the operation of equipment under sustained acceleration are most easily carried out on a centrifuge or rotating platform. The acceleration experienced by equipment on a centrifuge is given by: $4\pi^2n^2r$ ft/sec.^{2}; where n is the speed of rotation in r.p.second; and r the perpendicular distance in feet from the axis of rotation. Power supplies and monitoring of the equipment can be arranged by using a bank of slip rings on the axis of rotation. For simulating the conditions existing in a missile which is being accelerated by booster rockets, rocket-driven sleds running on guide rails are used. Such sleds experience vibration and shock in addition to steady acceleration and are more representative of rocket flight conditions than the centrifuge. Such equipment is expensive to operate and has not yet been extensively used for aircraft work.

CHAPTER 4

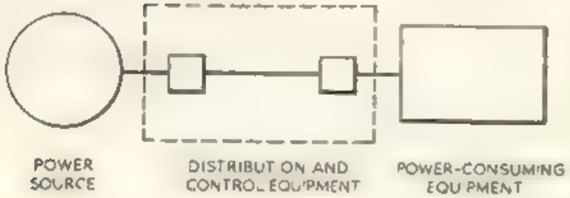
Components of an Aircraft Power System

THE simplest power system is represented in Fig. 4.1. The component parts, identified by their functions, are (*a*) power source; (*b*) distribution and control equipment; (*c*) power-consuming equipment. Power sources are invariably generators, a.c. or d.c., and are almost without exception driven by the main engines of the aircraft. Except in the case of small single-engined aircraft, two or more generators are installed, being connected in parallel or else provided with change-over arrangements to ensure that essential equipment can be supplied with power in the event of one generator failing.

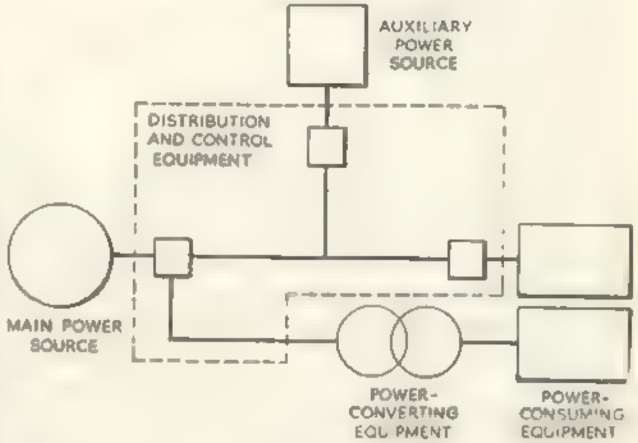
Equipment for distributing and controlling power comprises busbars, connectors, switches, contactors and fault-protection devices. Study of this equipment is important firstly because its weight is a little more than one-third of the total weight of electrical equipment, and secondly, because the reliability of the system depends very much on the arrangements for detecting and clearing faults. Apart from maintaining continuity of supply in the event of a fault, it is necessary to check short-circuit faults very quickly in order to minimize the risks of fire and damage to the aircraft structure.

Power-consuming equipment, sometimes termed utilization equipment, includes all the equipment on the aircraft which uses electrical power. The services or functions performed by this equipment are the only reasons for the existence of an electrical power system and, as may be expected, the power requirements of this equipment largely determine the design of the system. Power-consuming equipment is of divers types such as motors, heaters, lights and electronic equipment, and it is usual to find that both a.c. and d.c. power is required and that several different voltages, frequencies and numbers of phases are also required. Power in these various forms is usually obtained from converting equipment, a class of equipment not present in the simple system shown in Fig. 4.1, but in addition to convertors some aircraft have two or more generators providing a.c. and d.c. power.

Converting equipment comprises such things as rotary transformers for



(Left) FIG. 4.1. *Block diagram of a simple power system.* (Below) FIG. 4.2. *Block diagram of aircraft power system.*



changing voltage levels and also for changing d.c. to a.c.; motor generators for frequency conversion, static transformers and rectifiers. A more developed power system, including some power-converting equipment, is shown in Fig. 4.2.

Another class of equipment shown in Fig. 4.2 is that used for providing power when the primary sources are inoperative, either through failure or when the main engines are not running. Auxiliary sources of power have usually taken the form of accumulators, but recent developments of small prime movers, together with the increasing use of a.c. systems have hastened the development of auxiliary generating plants (A.G.P.) which also perform this function.

Each of these classes of equipment, which constitute the components of a power system, will be discussed in the following chapters.

Chapter 5. Power Sources: D.C. Generators.
Chapter 6. Power Sources: A.C. Generators.
Chapter 7. Auxiliary Power Sources.
Chapter 8. Power-converting Equipment.
Chapter 9. Power-consuming Equipment.
Chapter 10. Power Distribution and Control.

The integration of these equipments to form complete systems follows in Chapter 11. A number of topics such as the electrical arrangements for crash-landing and fire-detection systems, which do not conveniently find a place under these headings, are covered in Chapter 12.

CHAPTER 5

Power Sources: D.C. Generators

AIRCRAFT d.c. generators are all self-excited shunt-field generators, but a.c. generators, although nearly all salient-pole rotating-field generators, are used with several different methods of excitation and in several modified forms. Direct-current generators have been used from the first, but a.c. generators have only become widely used since early in the second world war. Initially, the choice of d.c. generators was determined by the fact that a d.c. generator can operate satisfactorily in parallel with an accumulator, but an alternative generator was sought when electronic equipment, such as radar equipments, became a major electrical load. Considerable emphasis was given to this change by the shortcomings of the d.c. generator when it is designed for high output and minimum weight.

Principally, these shortcomings are in the process of commutation, which is spoiled by the effects of small mechanical imperfections which become evident at high speeds; it is also adversely affected by the atmospheric conditions at high altitude and by high temperature. Despite these things d.c. generators are still used in greater numbers than a.c. generators, but mainly in the smaller ratings. It is likely that they will continue to be used in the future, probably in aircraft where the required total generator capacity is less than 50 kW and which do not fly at altitudes exceeding 20,000 feet.

Operation of d.c. generators is usually required over a range of speed corresponding to the speed range of the aircraft main engines. This depends very much on the type of engine and duty of the aircraft, but full generator output is often required over a range as wide as 4 to 1, that is, the highest speed being four times the lowest speed. The requirement for power at the lowest engine speeds, which occur during taxying and in some cases during approach glides prior to landing, is becoming more severe as airport traffic increases and as navigational and landing aids come into general use. Since it is the lowest speed at which full output is required which determines the size and weight of the generator, the higher speeds at which the generator is required to operate during flight are only an embarrassment to the designer, and one which the industrial designer does not usually have to face. This wide operating speed range and the requirement for minimum weight are the two

principal things which give rise to differences between the design of d.c. generators for aircraft and those for industrial purposes.

Voltage regulation to control the voltage of the aircraft system within acceptable limits under all load and speed conditions, is effected by an automatic shunt-field regulator. Self-regulating generators were used in some early aircraft, but the extent of the load and speed changes occurring in modern aircraft together with the need for weight saving have rendered this type of generator impracticable. In the following sections the theory of d.c. generators is briefly reviewed and the aspects which relate to designing for light weight, wide-speed-range operation and automatic voltage control are discussed in detail.

No-load or Open-circuit Characteristics. The relationships between the terminal voltage of a generator and the field or excitation current are shown in Fig. 5.1 for three typical speeds. From these curves some important facts may be deduced. Firstly, at any one speed the field current may be used to control generator voltage. Secondly, the change of voltage, following a change of speed, may be prevented if the field current is changed simultaneously. Consider the curve for 3,300 r.p.m.; a field current of 1·35 amp. gives 28 volts. If the speed is increased to 6,000 r.p.m. the voltage rises to 51·5 volts but may be restored to 28 volts by reducing the field current to 0·6 amp. The task of adjusting the generator field current in order to maintain constant voltage at all generator speeds is one of the functions performed by the voltage regulator.

The curves of Fig. 5.1 show clearly the small voltage generated when the field current is zero, this voltage being caused by residual magnetism in the yoke and poles of the generator. Its existence is essential for self-excitation and the generator must be designed and installed so that the residual magnetic flux is never eliminated or reversed. It can also be seen that, particularly at higher speeds, the generated voltage can be very much greater than the rated voltage of the generator. The occurrence of such voltages in the aircraft

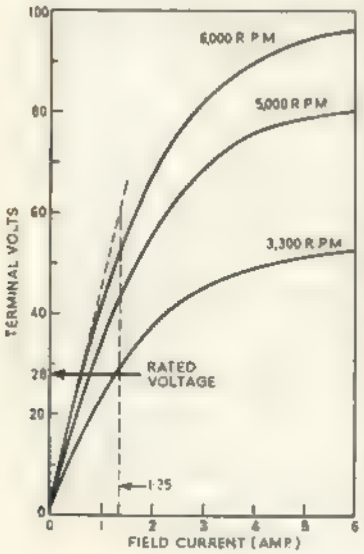


FIG. 5.1. *No-load characteristics of a 28-volt aircraft generator. These curves show that at the higher speeds the generated voltage can be much greater than the rated voltage.*

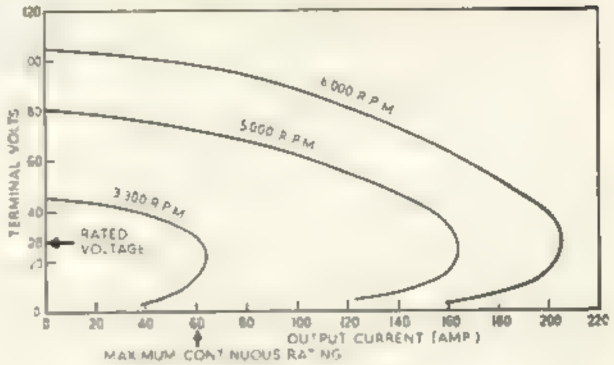


FIG. 5.2. *Curves relating terminal voltage and output current of an aircraft d.c. generator rated at 1,680 watts. Field-circuit resistance is constant at 15 ohms.*

system must be prevented by appropriate design of the voltage regulator and, in the event of a regulator failure, by over-voltage protection equipment.

Load Characteristics. The terminal voltage and output or load current are related as shown in Fig. 5.2. The initial downward slope of these curves is caused by armature resistance and armature reaction. In aircraft generators both armature resistance and the effect of armature reaction are high, the first because the cross-sectional area of the armature conductors is small, and the second because the field coils are small. Both these features are incorporated into the generators because they achieve some reduction in weight. Thus the change of terminal voltage with a change of output current is large, and adjustment is required to the field current if constant voltage is to be maintained. The task of adjusting field current to maintain constant voltage under all load conditions is the second function of the voltage regulator, which is combined automatically with the first, adjustment for speed changes.

When a generator is controlled by a voltage regulator the output curves are modified as shown in Fig. 5.3. Point *A* is the normal full-load condition which may be obtained at any speed within the range 3,300 to 6,000 r.p.m. At lower speeds the rated output is not obtainable without exceeding the rated value of field current. Higher speeds are not permitted for mechanical reasons but if this is disregarded, output at higher speeds may also be found

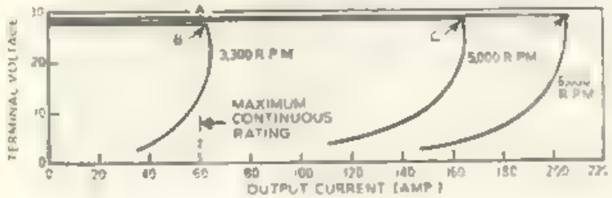


FIG. 5.3. *Curves relating terminal voltage and output current of a generator fitted with a voltage regulator.*

to be unstable. This is because the value of field current required is very small and small fluctuations in the field current cause unusually large fluctuations of output voltage. The higher currents available as indicated by points *B*, *C*, and *D* represent overloads for the generator and, if permitted to flow continuously, would cause excessive heating of the armature conductors and sparking at the commutator.

Most aircraft generators are rated to deliver overload currents for short periods, but this is generally regarded as a facility for use only in an emergency. Typical overload ratings are between 25 and 50 per cent for 5 minutes. It is important to remember, however, that should a short-circuit occur, the generator can deliver a current much greater than its rated current. At points *B*, *C* and *D* the voltage regulator is permitting the maximum values of field current attainable with the generator self-excited. Any attempt to increase the loading beyond the values indicated by these points results in the voltage falling below the required value. Ultimately, both voltage and current are decreased by overloading, and the generator output is reduced to an unacceptably low level.

In the event of the regulator failing to control, Fig. 5.2 shows that at 6,000 r.p.m. the output voltage can rise to nearly four times its rated value, even when the generator is delivering its rated current. Under these conditions a power output of more than 10 kW is possible, six times the rated output.

Voltage Regulation. From the no-load and load characteristics it has been deduced that it is possible to control the voltage of a d.c. generator to a predetermined value under all conditions of load and speed. This is true for any d.c. generator, but to be suitable for aircraft some consideration must be given to the design of the generator so that it can be self-excited and controlled with an aircraft-type voltage regulator. It is a desirable design criterion that the field magneto-motive force (m.m.f.) shall be larger than the full-load armature m.m.f. in order to secure good commutation, good natural regulation and stable output voltage. The field m.m.f. is given by the product of field current, i_f, and field winding turns, T_f; that is i_fT_f.

Aircraft regulators have not been developed to control large values of current, and this sets an upper limit to the practical value of i_f. There is also an upper limit to the value of T_f which is not so easily explained. Firstly, consider the resistance, r_f, of the field windings. This is approximately proportional to the number of turns, T_f, unless the cross-sectional area of the wire is increased as T_f is increased. However, the use of larger wire is impracticable because of the increased volume of the windings and therefore of the size and weight of the generator. Thus T_f can be increased only if r_f can also be allowed to increase. This again is impracticable because the voltage available for the field winding of a self-excited generator is necessarily less

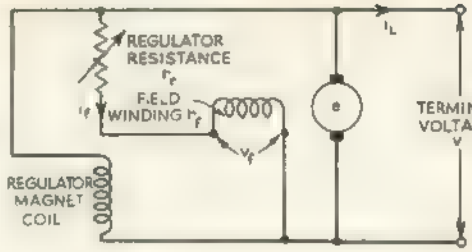


FIG. 5.4. *Circuit of a self-excited d.c. shunt generator with field-regulating resistor and a regulator magnet, or sensing coil.*

than the output voltage. It is less because of volt drops in the field-circuit wiring and the regulator resistance. Ideally, the latter could be reduced to zero when required, but in practice, aircraft regulators have significant minimum resistance values. Thus both i_f and r_f are restricted below certain maximum values, the former because of regulator current limitations and the latter by the available field-circuit voltage, and in consequence the maximum value of field m.m.f., i_fT_f, is also restricted. Although this is an embarrassment to designers there is no possibility other than to design within this restriction.

In the early generators, in which shunt-field windings were the only windings carried on the stator, it was usual to find the available winding space entirely devoted to the shunt-field winding in order to achieve the highest i_fT_f. In later machines, where the armature m.m.f's. are higher, it has been found essential to use some of the space for compensating windings to neutralize the armature m.m.f., and for interpoles to provide close control over the commutating conditions.

One of the conditions for self-excitation of a d.c. shunt generator is that the total resistance of the shunt-field circuit shall be below a certain critical value. It may be seen from Fig. 5.4 that, in addition to the resistance of the shunt-field winding itself, this includes the regulator resistance, the armature winding, brush and brush-contact resistances, and the resistance of intermediate wiring. The critical value depends on speed and may be determined from the slope of the initial part of the no-load characteristic, as shown by the broken line in Fig. 5.1. For that case, at 6,000 r.p.m., the critical value is 60/1·35 which is approximately 44·5 ohms. At 5,000 and 3,300 r.p.m. the critical values are approximately 34 and 24 ohms respectively. Generally the total shunt-field circuit resistances in aircraft installations are safely below the critical values, even at the lowest operating speeds, but a low value of shunt-field winding resistance contributes to the safety margin.

Conditions necessary for self-excitation with correct polarity may be summarized as follows: (*a*) the existence of residual magnetism of adequate strength and correct sense; (*b*) shunt-field circuit resistance must be less than the critical value; (*c*) adequate speed of rotation, since the critical value of

shunt-field circuit resistance decreases as the speed increases; (*d*) correct direction of rotation; (*e*) correct sensing of shunt field connexions.

Loss or reversal of residual magnetism has sometimes been observed after major system faults. This is because large fault currents flowing in the armature, and windings in series with the armature, set up unusually large m.m.f.s which, under some conditions are demagnetizing. To ensure positive excitation, some installations include a field "tickling" or "flashing" circuit which momentarily energizes the field circuit in the correct sense at the time of switching on the generator.

TRANSIENT CONDITIONS

So far the control of generators has been considered only under steady-state conditions when such quantities as load current, speed and field current have reached steady values. During changes of these quantities several effects come into play which are not apparent in the steady state. These effects are called transient effects and the periods during which they are present are called transient periods. To appreciate the nature of transient effects consider a self-excited shunt generator without a regulator, which is being driven at constant speed and which is delivering ¾ full load. The following sequence of events will occur during the transient resulting from an increase of load resistance such that when normal voltage is restored the generator delivers only ¼ full-load current. Firstly, the load current will be reduced, and simultaneously the generator terminal voltage will rise owing to the reduced armature voltage drop. However, the reduction of load current will be delayed by the combined inductance of the armature winding and load circuit.

The manner of this delay is indicated by the current curve in Fig. 5.5 between the times t_0 and t_1. It is caused by induced e.m.f. in the inductance, the induced e.m.f. being proportional to the rate of change of current. This induced e.m.f. is superimposed on the generated e.m.f. and appears at the generator terminals as shown by the voltage curve in Fig. 5.5. Throughout the interval of time t_0 to t_1 it may be assumed that the flux in the generator has not changed appreciably. This will be nearly true because any sudden change of flux will give rise to induced currents, or eddy currents, in metal parts of the

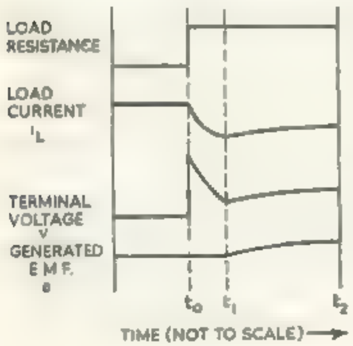
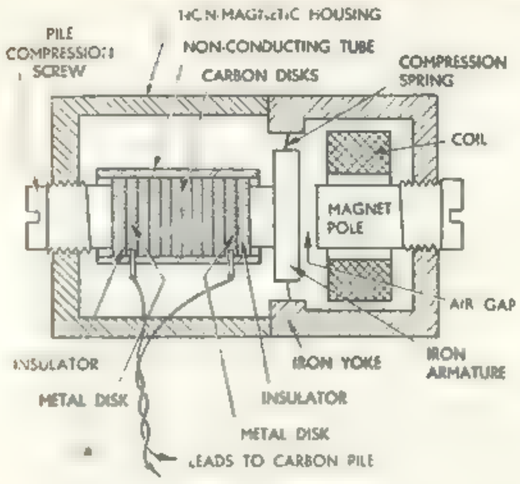


FIG. 5.5 *Illustrating the changes of generator output immediately following a reduction of load.*



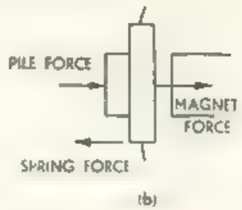


FIG. 5.6. (a) *Carbon-pile regulator, showing the three forces* (b) *acting on the iron armature.*

generator which lie in the flux path, and these eddy currents will tend to maintain the flux at its original value. When the eddy currents die away, the flux in the generator will increase slightly owing to reduced armature reaction. Also, the effect of increased terminal voltage will be to increase the generator field current, although this increase will be very much delayed by the large inductance of the field winding.

The effects of both reduced armature reaction and increased field current are shown by the rising curve for generated e.m.f. between the times t_1 and t_2 in Fig. 5.5. Terminal voltage and output current curves for the same period rise in a similar manner. The length of the period t_1 to t_2 is determined mostly by the ratio inductance/resistance, or *time constant* of the field circuit, which may be about 0·1 second. This should be shown in Fig. 5.5 to be about a hundred times longer than the period t_0 to t_1 which is determined mostly by the time constant of the armature and load circuit.

A voltage regulator, if it had been connected, would have begun to operate at some time after the onset of the transient period. Owing to the inductance of the voltage-regulator sensing circuit and mechanical inertia of the regulator armature, a carbon pile type of regulator (see Fig. 5.6) would not have any significant effect before the time t_1, but would probably have restored the voltage to normal before the time t_2, that is, in rather less than 0·1 second.

It may be seen that such quantities as field and armature circuit inductances and mechanical inertia in a regulator have a large influence on the way in which a generator output deviates from normal immediately after a change. The calculation of the transient behaviour of generators and regulators is best attempted by servo-mechanism techniques since the generator

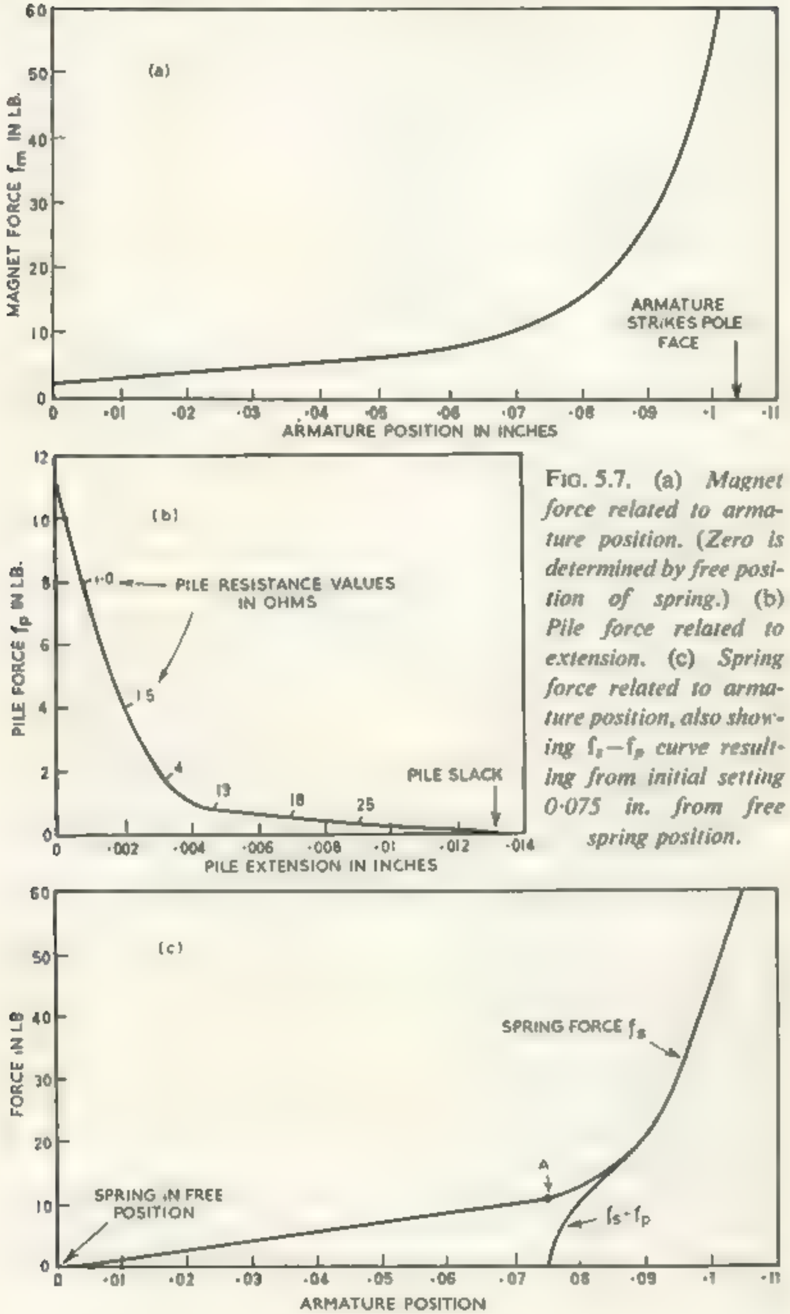


FIG. 5.7. (a) *Magnet force related to armature position. (Zero is determined by free position of spring.)* (b) *Pile force related to extension.* (c) *Spring force related to armature position, also showing* $f_s - f_p$ *curve resulting from initial setting 0·075 in. from free spring position.*

and regulator constitute a closed-loop or feed-back system. The accuracy of such calculations is often not very good because it is difficult to take account of all the significant effects such as those caused by temperature changes of the carbon pile and regulator mechanism. Non-linear relationships, such as the relationship between pile resistance and pile pressure shown in Fig. 5.7 (*b*), cause difficulty because they are not easy to express mathematically. The alternative to calculation is experiment on actual equipment. In the early stages of system design when the proposed equipment does not always exist, this also has its difficulties. Nevertheless, experiment on full-scale systems is becoming an increasingly common practice.

VOLTAGE REGULATOR: CARBON-PILE TYPE

An essential component of a regulator is a resistor, suitable for carrying the generator field current, and of such a form that its ohmic value, r_r, may be changed with changes of generator voltage.

It has been explained in a previous paragraph (see *Voltage Regulation*) that the field-winding resistance, r_f, must be low and that this is an embarrassment because it is one of the things which limits the number of field turns. It was also pointed out that a small minimum value of regulator resistance, r_r, helps to relieve the position by increasing the maximum available field-coil voltage, v_f. Another aspect of this is that the maximum field current, i_f, is determined partly by the minimum value of r_r. If this is too great to allow the rated value of i_f, the generator will be unable to deliver full load at minimum speed. Thus it is desirable to be able to reduce r_r to zero, but in aircraft practice in which a carbon pile is used as the variable resistor, this cannot be achieved. The regulator resistor must also have a maximum value great enough to restrict i_f to the low value required at maximum speed and light load.

The generator to which Figs. 5.1, 5.2 and 5.3 refer has a maximum rated field current of 2·2 amp. and requires a minimum field current of 0·6 amp. The latter value occurs at 6,000 r.p.m. on no-load, as may be read from Fig. 5.1. Thus the total field-circuit resistance must be varied between 28/0·6 and 28/2·2; that is, 46·7 and 12·7 ohms. Since the field-winding resistance is about 7 ohms, the regulator resistor must be variable between (46·7—7) and (12·7—7); that is, about 40 and 6 ohms. A slightly greater range than this is necessary to allow for the change of resistance of the field windings with temperature, the resistance of wiring and connexions in the field circuit, and slight variations of the value of the regulated voltage.

This requirement for a wide range of values has proved difficult to meet and many years of development have been necessary on this as well as on other aspects of the regulator. Modern regulators, except those for use with very small generators, employ a pile of carbon disks as the variable resistor.

The resistance of such a pile changes with applied mechanical pressure, being least, though not zero, when the pile is tightly compressed, and greatest when the pile is slack. The greatest resistance value which can be used is that obtained with the pile pressure just sufficient to prevent the disks moving under vibration or shock. A typical range of useful values is 60 ohms to 4 ohms.

A simplified diagram of a regulator is shown in Fig. 5.6 (*a*) and, as indicated in (*b*), there are three forces acting on the armature of the regulator. The spring force, f_s, tends to compress the pile; the magnet force, f_m, and

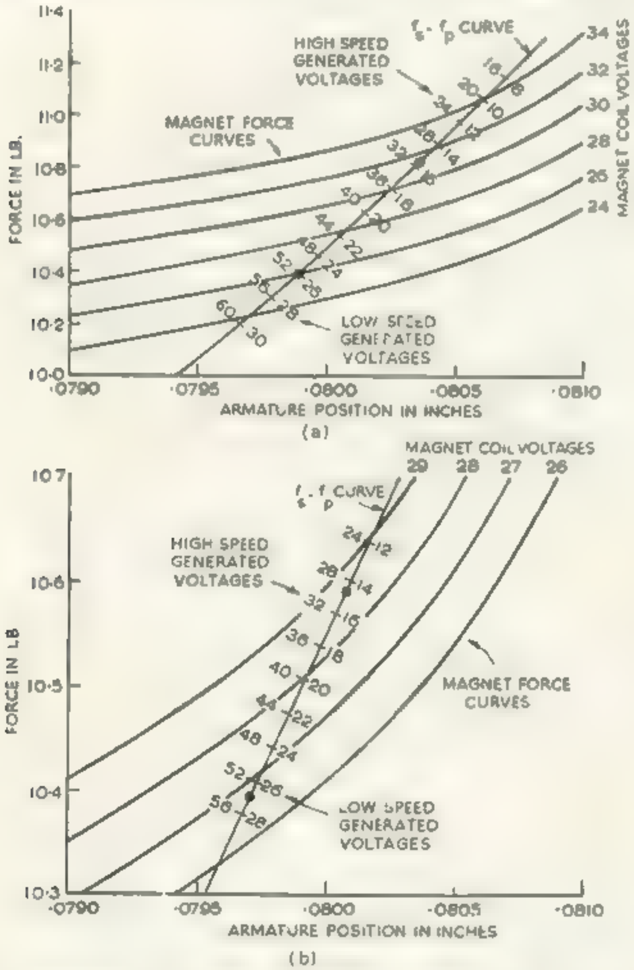


FIG. 5.8. (a) *Mechanical and electrical operating conditions at two generator speeds.* (b) *Showing the improved regulation with* $f_s - f_p$ *and* f_m *curves of similar slopes.*

the resilience of the carbon disks, both tend to expand it. The armature is free to move in the direction of the pile axis and in steady operation takes up a position where the forces balance, that is, where

$$f_p + f_m = f_s \qquad (1)$$

or

$$f_p = f_s - f_m \qquad (2)$$

where f_p is the force arising from the resilience of the carbon disks.

From (2) it can be seen that if f_m is made to increase with generated voltage, a rise in voltage will reduce the pile force, f_p, and increase the pile resistance. Thus if the pile is connected in a generator field circuit the generator voltage will be reduced towards its former value. The circuit shown in Fig. 5.4 secures this result. This description of regulator operation is over-simplified but is given because it is useful to have an idea of the general mode of operation when considering the details.

A more precise understanding of the regulator may be obtained by examining the three forces and the way in which they are related to generator voltage and armature movement. Firstly, the magnet force, f_m. This is given approximately by the equation

$$f_m = \frac{Kv^2}{l_g^2} \qquad (3)$$

where v is the magnet coil voltage, which is also the generator terminal voltage; l_g is the length of the air gap between the armature and the magnet pole; and K is a constant which depends on the fixed dimensions of the regulator, and the magnet coil design. K includes the coil resistance and will therefore be affected by temperature changes. A practical curve relating f_m and armature position is shown in Fig. 5.7 (*a*). The curve is true only for one value of voltage, since from equation (3), the force varies as the square of the voltage. A family of f_m curves for a range of voltage is shown in Fig. 5.8 (*a*).

The relationship between the force, f_p, applied to the carbon pile and its change of length is of the form shown in Fig. 5.7 (*b*). Each point on the curve indicates not only a value of f_p and the corresponding pile extension, but may also be identified by a particular value of pile resistance. Typical values are indicated along the curve. When the pile is connected in the field circuit of a generator it is equally true that each point on the curve corresponds to a particular value of generated voltage, provided that generator speed and load are constant. Notice the scale of the pile extension axis, which indicates that the change of pile length can be very little more than 0·01 in.

Finally, the curve of spring force, f_s. The spring is designed to have a force curve which intersects the magnet curve for the required generator voltage, at an armature position where the air gap is small. This is necessary in order to obtain a sensitive regulator which will control generator voltage within a very small range regardless of large changes of speed and load. It is

also designed to intersect at a small angle, again to secure sensitivity. A typical curve is shown in Fig. 5.7 (*c*).

The regulator is initially set up by tightening the pile compression screw, shown in Fig. 5.6 (*a*), and compressing the pile against the spring. Suppose the armature is moved 0·075 in. from the natural or free position determined by the spring, then from point *A* in Fig. 5.7 (*c*) the spring force, f_s, is 11 lb. If the magnet is not energized, the pile force, f_p, is equal to f_s although acting in the opposite direction; f_p is therefore also 11 lb. When the regulator is connected to a generator and the magnet is energized, the armature is moved further towards the pole, against the spring, by the magnet force, f_m, and the pile is partially decompressed. If the regulator is stable and correctly adjusted, the armature will take up a position where two conditions of equilibrium are satisfied: (*a*) the mechanical forces are balanced so that

$$f_m = f_s - f_p \qquad (4)$$

which is a simple rearrangement of equation (1); and (*b*) the voltage corresponding to the pile resistance is exactly equal to the generator terminal voltage which is applied to the magnet coil.

The armature position and generator voltage at which these two equilibrium conditions occur can be determined by superimposing the curves for f_m and $f_s - f_p$ as shown in Fig. 5.8 (*a*). Only the operating regions of the curves are plotted in order to use enlarged scales. The curve for $f_s - f_p$ is derived, as indicated in Fig. 5.7 (*c*), by subtracting ordinates corresponding to f_p from the curve for f_s. At point A, $f_s = f_p = 11$ lb., and $f_s - f_p$ is zero. This is the condition to which the regulator was initially adjusted. At another point, say 0·077 in. from the origin, to which f_m may move the armature, the pile has been extended by 0·002 in. From Fig. 5·7 (*c*), f_s is increased to about 11·5 lb. and from Fig. 5.7 (*b*), f_p is reduced from 11 to 4 lb. Thus $f_s - f_p = 11{\cdot}5 - 4 = 7{\cdot}5$ lb.

Similar consideration of other armature positions enables a number of points on the $f_s - f_p$ curve to be found. Notice that after an armature movement of only 0·013 in. from 0·075 to 0·088 in. from the origin, the pile is completely slack and $f_s - f_p = f_s$. The working range of armature movement is therefore only a few thousandths of an inch, as indicated by the armature position scale of Fig. 5·8 (*a*). Points on the $f_s - f_p$ curve, like the f_p curve, correspond to values of pile resistance and generator voltage. Voltages are indicated along the curve in Fig. 5·8 (*a*).

Mechanical equilibrium is indicated by the intersection of the $f_s - f_p$ curve with the f_m curve appropriate for the generator voltage, but the second condition for equilibrium requires that the point of intersection on the $f_s - f_p$ curve also corresponds to the generator voltage. Of the several intersections in Fig. 5.8 (*a*) only that indicated at 26 volts satisfies both conditions; the high-speed generated voltages on the left-hand side of the $f_s - f_p$ curve

should, for the present, be ignored. At the operating conditions indicated by this intersection the forces f_m and $f_s - f_p$ are each equal to nearly 10·4 lb., and the pile pressure and resistance are such that 26 volts is generated, which is precisely the voltage required to give rise to the intersecting f_m curve.

The effect of a speed change on the operating conditions may be taken into account by adjusting the voltage scale along the $f_s - f_p$ curve. It is convenient to suppose that the speed is doubled, since it is then approximately true that the voltage generated with any particular value of pile resistance, is also doubled. In Fig. 5·8 (*a*) the doubled voltages are shown along the left-hand side of the $f_s - f_p$ curve and a new intersection may be found at 31·4 volts.

The change of generator voltage with speed is one measure of the regulator sensitivity which—in the example considered—is not very good, being 26 to 31·4 volts. It can be improved by designing the regulator so that the slopes of the f_m and $f_s - f_p$ curves are nearly the same. This may be checked by redrawing the f_m curves of

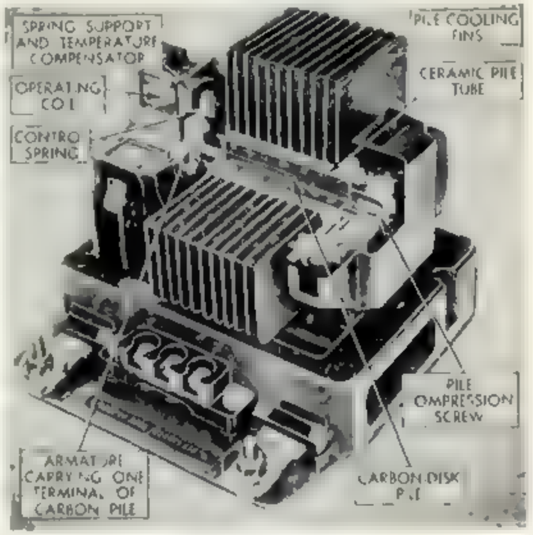


FIG. 5.9. *Sectional view of a carbon-pile regulator.* (Below) *A transistor circuit, together with a carbon pile, constitutes a d.c. voltage regulator.*

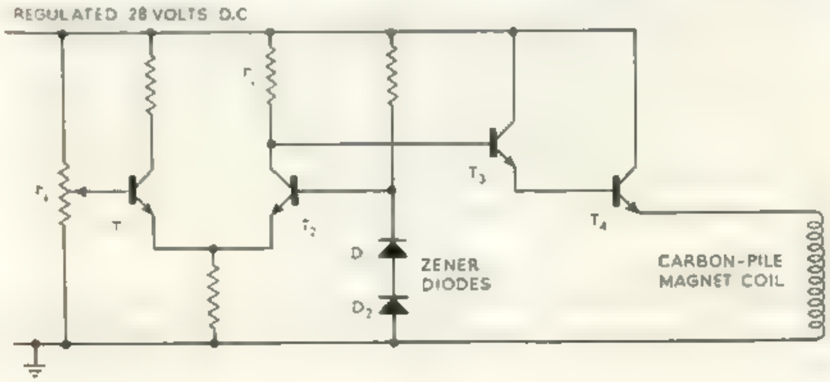


Fig. 5.8 (*a*) and superimposing an $f_s - f_p$ curve of lower slope, as shown in Fig. 5.8 (*b*). The new equilibrium voltages are 26·8 and 28·7 volts, which is a considerable improvement. Unfortunately if the two curves should become parallel, or if the slope of the $f_s - f_p$ curve should become less than that of the f_m curves, the regulator will be unstable and assume an extreme position giving either very high or very low voltage. The effects of temperature and ageing of the spring, and the effects of temperature, humidity and wear on the carbon-disk pile are among the many things which cause changes of slope. It is therefore unsafe to design for slopes which are too nearly alike, and much of the development of the regulator has been aimed at securing sensitivity without risking instability.

Other forms of instability can arise and oscillation of the generator voltage after changes of load is one that has commonly occurred. Damping by air and oil dashpots has been used to check this effect, air giving way to oil for high-altitude aircraft. Stabilizing transformers which provide inductive coupling between the generator field circuit and the regulator sensing coil are also used. The connexions of the transformer are such that a sudden change of field current induces a voltage in the sensing circuit which tends to operate the regulator in such a manner as to offset the effect of the field current change. Since the output from a transformer is proportional to the rate of change of current in its primary winding, the stabilizing transformer has no effect except under rapidly changing conditions. Stabilizing transformers do not generally give quite such good results as the best oil dashpots.

A sectional view of a regulator is shown in Fig. 5.9 in which the arrangement of the essential components may be seen. The insulating tube containing the pile is fitted with large cooling fins; this permits the wattage rating of the pile to be substantially increased. Carbon piles are available for working with dissipations up to 300 watts, provided cooling air is blown through the fins. This particular regulator is suitable for use with the 6 kW Rotax generator shown in Fig. 5.14. The regulator has a pile rating of 210 watts, if blast-cooled, and weighs 7½ lb., about one-sixth of the weight of the generator.

A form of overcurrent protection adopted for generators in some early systems used a second carbon pile in the generator field circuit. This pile was normally compressed and its magnet coil was in series with the generator and carried the output current. The design was such that the pile pressure was reduced sufficiently to cause a substantial reduction of generator output voltage at a current a little in excess of the rated output.

TRANSISTORIZED CARBON-PILE VOLTAGE REGULATOR

In this arrangement the function of the carbon pile and its associated magnet and spring system is simplified from that of regulation to current control. When used as a regulator, it senses the generated voltage, compares

it with a reference which is inherent in its design and setting, and adjusts the generator excitation current in a manner depending on the difference between the generated voltage and the reference. When used in conjunction with transistor circuitry it receives coil current which is directly related to the value of excitation current required. Thus it is not necessary for the spring force and the magnet force to be related in the intricate manner described in the previous section. It is only necessary that an increased coil current should cause an increased pile resistance and vice-versa.

The adjustment of the magnet coil current is effected by a circuit such as that shown in Fig. 5.9. A reference voltage, which is very nearly constant over wide ranges of temperature and generated voltage, is developed across a pair of zener diodes, D_1 and D_2. (Zener diodes are briefly described in the Section on the Transductor Voltage Regulator, page 71.) Two diodes are used because it is relatively easy to select a pair which have compensating temperature coefficients. A fraction of the generated voltage, having a similar value to the reference voltage, is selected by the potentiometer, r_1, and this, together with the reference voltage, is passed to a difference amplifier which includes transistors T_1 and T_2.

The output from the difference amplifier, the potential of the lower end of r_2, is arranged by circuit design and adjustment of r_1 so that it controls the coil current, via the current amplifiers T_3 and T_4, at the value necessary to generate the required voltage. Changes of generated voltage cause proportional changes at the slider of r_1 and amplified changes of coil current. With this circuit and a carbon pile, the steady-state generated voltage can be maintained at about $\pm\frac{1}{2}$ per cent of the nominal value whereas with the carbon-pile regulator alone it is difficult to maintain closer control than $\pm 2\frac{1}{2}$ per cent over typical ranges of temperature and operating conditions.

It may be observed since the regulator magnet coil current can be controlled by a transistor, T_4 in Fig. 5.9, the generator excitation current could also be controlled directly by a transistor. At present carbon piles are capable of controlling larger currents and dissipating greater powers than practical transistors but the development of high-power transistors capable of replacing carbon piles appears probable.

An experimental method of controlling generator field current with the available resistors is described in an Institution of Electrical Engineers paper entitled *Transistors for the Regulation of Aircraft Power Systems*, by K. F. Bacon (see Reference 23, page 313).

COOLING

Before discussing the cooling of aircraft d.c. generators in particular, it is intended to consider some of the basic facts of cooling. Firstly, let us consider how heat is generated in electrical machines. The principal cause is

almost invariably the passage of current along the conductors which is accompanied by the conversion of some electrical energy into heat. The lost electrical energy is often called the "copper loss". It may be calculated by any of the following expressions:

$$w = i^2r = v^2/r = iv \qquad (5)$$

where w is the rate, in watts, at which heat is developed; i is the current in amperes; v is the volt-drop across the conductors; and r is the resistance of the conductors in ohms.

The resistance, r, will change with temperature and the exact calculation of this source of heat in a machine will have to take account of this effect. It becomes particularly significant in machines operating over wide temperature ranges: a change of 100 Centigrade degrees causes a change of resistance of copper conductors of approximately 43 per cent, a fact which may be easily remembered as $\frac{1}{2}$ per cent per Centigrade degree. The formula for calculating the change of resistance with temperature is:

$$r_2 = r_1\{1 + \alpha(T_2 - T_1)\} \qquad (6)$$

where r_1 is the resistance at the initial temperature T_1; r_2 is the resistance at the final temperature T_2; and α is the temperature coefficient for the conductor material (0·00428 for copper).

In aircraft machines this source of heat is not merely tolerated but is designed to be several times larger than in conventional machines, because by accepting heavy copper losses it is possible to reduce weight. This follows from the fact that the resistance of a conductor is inversely proportional to the conductor cross-sectional area, whereas the weight of a conductor is proportional to the cross-sectional area. The formulae for comparing resistance and weight are:

Resistance in ohms, $\quad r = \rho l/a \qquad (7)$

where ρ is the specific resistance of the conductor material in microhm-centimetres (1·72 for annealed copper at 20 deg. C.); l is the conductor length in cm.; and a is the conductor cross-sectional area in square cm.

Weight in grams, $\quad w = \sigma l a \qquad (8)$

where σ is the density of the conductor material in grams per cu. cm. (8·93 for copper). The use of conductors of relatively small cross-sectional area results in full-load current densities of between 10 and 20 amp. per sq. mm.

In conductors carrying a changing current, such as those in the armature of a d.c. generator, additional heat will be generated owing to circulating currents, or eddy currents, in the conductor. This effect could give rise to large quantities of heat in some aircraft machines, where high speed of rotation causes a high frequency of current changes, but by suitable choice of conductor dimensions the heat is kept to a fairly low level.

The second greatest source of heat is in the iron which carries varying magnetic flux. Heat appearing in the iron, the "iron losses", is generally

substantially less than that arising in the conductors under full-load conditions, but is nevertheless significant. Unlike copper carrying a steady current, iron carrying a steady flux is not a source of heat. Iron carrying a changing flux is a source of heat for two reasons: magnetic hysteresis and the generation of eddy currents. Neither phenomenon has effects which are amenable to precise calculation, but the following formulae are generally accepted and give a useful indication of the way in which the losses depend on frequency and flux density.

Hysteresis loss, $w_h = K_1\hat{B}^{1\cdot6}f \times 10^{-7}$ watts per cu. cm. $\qquad (9)$

where K_1 is the hysteresis coefficient for the material carrying flux (a value for typical soft iron is 0·002); $\hat{B}$ is the peak value of flux density in gauss or lines per sq. cm.; and f is the frequency of flux alternations in c/s.

Eddy-current loss, $w_e = \dfrac{1\cdot65\,\hat{B}^2 f^2 d^2 \times 10^{-16}}{\rho}$ watts per cu. cm. $\qquad (10)$

where d is the thickness of the iron laminations in cm.; and ρ is the specific resistance of the iron in microhm-centimetres (for a low-loss iron such as Alphasil, ρ is about 50).

In practice the manufacturers of the more highly developed magnetic

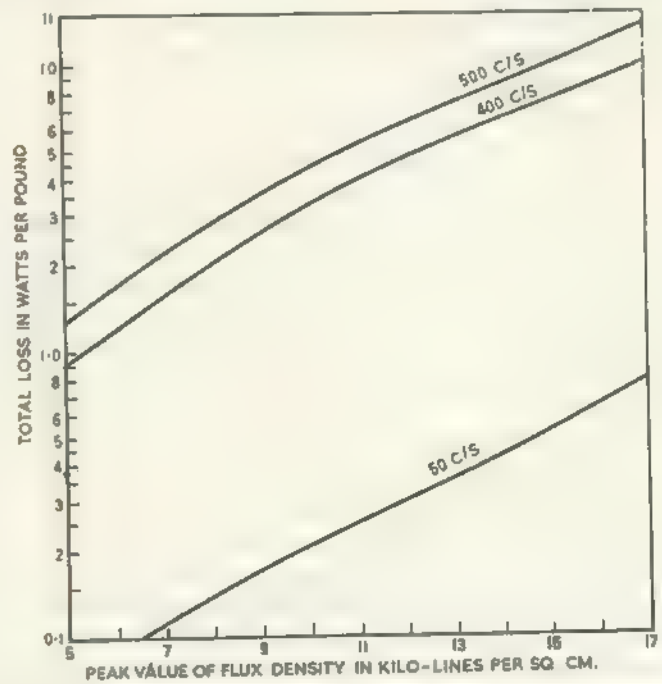


FIG. 5.10. *Curves for 0·004-in. Alphasil laminations, relating eddy-current and hysteresis losses to the peak value of sinusoidally changing flux density.*

materials for electrical machines supply curves showing how the combined hysteresis and eddy-current losses change with the variables, flux density and frequency, and these curves are generally used in preference to calculations. Typical curves are shown in Fig. 5.10 for laminations 0·004 in. (0·01 cm.) thick of Alphasil grain-orientated silicon iron.

Despite the fact that both the losses are proportional to a power of the flux density, densities in aircraft machines are designed to be high. However, iron saturation sets a limit which is not very much above conventional values. Frequencies of flux alternations are high owing to high rotational speeds and, as a result of this and the slightly higher than normal flux densities, aircraft machines do have high iron losses.

Another source of heat is friction at bearings, oil seals and carbon brushes. This is relatively important in aircraft machines since the heat generated is directly proportional to speed, as is indicated by the following formula:

$$\text{Heat generated, } w_f = 2\pi nF \times 981 \times 10^{-7} \text{ watts} \qquad (11)$$

where n is the speed of rotation in r.p.second; and F is the friction torque in grams-cm. Oil seals which have felt or leather rings bearing on the rotating shaft may have excessive friction torques and not all types are suitable for aircraft generators.

The most immediately damaging effect of excessive heating is the deterioration of the insulation. Using the best materials that are commonly available, which are discussed in Ref. 22, it is practicable to operate aircraft machines at temperatures up to about 250 deg. C. The effects of heating on dimensions must be considered in the course of design. Differential expansion of the stator and rotor necessitates freedom for axial movement at one of the bearings. This is illustrated in Fig. 5.15 where a roller bearing is fitted at the commutator end. Differential expansion is to be expected because armature heating depends primarly on the generator load whereas stator heating is dependent on field current, the value of which changes with operating speed. Expansion of the commutators of d.c. machines is likely to cause distortion of the commutating surface, a problem which is discussed later (see *Commutators and Brushgear*).

The heating of magnetic materials causes only a small deterioration of their magnetic properties at the temperatures to which present insulating materials are restricted. The Curie temperatures of these materials are in the range 750 to 1,100 deg. C., and at these temperatures the magnetic properties are completely lost. High-permeability nickel irons are exceptional and may be seriously affected by temperatures only a little above 300 deg. C. Operation of the copper conductors at high temperatures is likely to cause oxidation and because of the increase of resistance with temperature, as defined by equation (6), also causes a further increase in copper losses. Oxidation may be avoided by nickel-plating the copper, but nothing can be done to prevent

the increase of resistance. Bearing lubrication is affected by temperature. For moderate temperature ranges greases are satisfactory, but at high temperatures forced lubrication with cooled oil is the only practicable method.

Before discussing methods of cooling it is worth while to examine the case of a machine for which no cooling is provided. The temperature of an uncooled machine, after t seconds of operation, is given by the equation:

$$\text{Temperature in deg. C., } T_2 = T_1 + \frac{wt}{WK_s} \qquad (12)$$

where T_1 is the initial temperature in deg. C.; w is the rate at which heat is generated in watts; t is the time of operation in seconds; W is the weight of the machine in grams; and K_s is the mean specific heat of the machine in joules per gram per deg. C. (a typical value is about 0·012).

It is practicable not to provide cooling for machines which are required to operate only for short periods. Starter motors, actuator motors and the generators of some guided missiles are typical examples. Equation 12 shows that, for the temperature T_2 to be low, the losses should be small but, as previously mentioned, it is usually necessary to accept high losses in order to minimize weight. The machine weight, W, obviously cannot be compromised very much, and K_s, the mean specific heat, is mainly determined by the copper and iron. Thus most of the effective terms in the equation are fixed by considerations other than heating, and the practical position is that it is only possible to dispense with cooling arrangements when t (the operating time) is short, say less than one or two minutes. Equation 12 takes no account of the fact that heat is generated non-uniformly inside the machine or that heat flow is not uniform in all directions. In practice, these things are important since they cause "hot spots" in the machine, so that equation 12 cannot be taken as the sole criterion when considering short-time operation.

Cooling by Conduction. Cooling may be achieved either by natural methods, by conduction, radiation or convection or, where these are inadequate, by artificial methods such as forced convection. Conduction alone is not greatly used as a method of cooling complete machines, partly because it is not a practicable method of removing heat quickly and partly because there are few large masses of cold metal available in aircraft, to serve as heat sinks. It is, however, the only method by which certain parts of machines can be cooled. The interior layers of a winding, for example, can be cooled only by conduction through adjacent layers. Attention is given to coil impregnation which, among other things, serves to improve coil cooling since the solid impregnant conducts heat very much better than do small air pockets. The cooling effect of conduction through the mounting flanges of some short-time-rated motors is significant, and it is sometimes specified by manufacturers as a condition of operation that the machines shall be

mounted on a component which can function as a heat sink. Similarly, but to a lesser degree, some heat may be conducted away by electrical connexions and through the mechanical shaft coupling.

Cooling by Radiation. Like conduction, radiation is not used as the sole method of cooling complete machines because it is not possible to radiate large amounts of heat from small surfaces without exceeding a safe temperature. Black unpolished surfaces radiate well, but polished surfaces do not; dull black surfaces readily receive radiated heat whereas polished surfaces reflect it. A blackened machine surface will assist cooling to a small degree provided the surrounding surfaces are at a lower temperature than the machine. When this is not the case, a heat-reflecting surface is preferable. Highly polished sheets of metal are sometimes interposed between hot surfaces, such as exhaust manifolds, and electrical machines, to reflect radiated heat before it reaches the machine.

Cooling by Natural Convection. Natural convection is not extensively used for large machines because in most cases the penalties of forced convection are small compared with the weight and volume which can be saved. For small static equipment, however, such as transformers and voltage regulators, natural convection cooling is common.

The cooling effect of air in natural convection currents arises because air in the vicinity of a hot surface becomes heated by conduction. The reduced density of the heated air causes movement which results in a flow of cold air past the hot surface. The velocity of flow is not uniform but varies from zero at the hot surface to a maximum value at some distance from the surface. The stagnant layer of air at the hot surface serves as a heat insulator and restricts the amount of heat which can be removed from the surface, since all the heat must pass through the stagnant layer by conduction. The conductivity of stagnant air is very low, approximately 10,000 times less than that of copper.

The heat which may be transferred by natural convection is proportional to the square root of the density of the cooling air. By reference to Fig. 3.1 it may be seen that at about 50,000 feet the air density is only 0·012 lb. per cu. ft. instead of nearly 0·08 lb. per cu. ft. at sea level. The cooling effect is therefore reduced to $\sqrt{0{\cdot}012/0{\cdot}08}=0{\cdot}39$ of the effect at sea level.

Forced Convective Air Cooling. Convection is the only method which lends itself to appreciable artificial improvement. This is achieved by increasing the velocity of the air over the hot surface until the air flow becomes turbulent instead of smooth or stream-lined. This change from smooth to turbulent flow occurs suddenly when a critical velocity is reached, the critical value depending on the duct dimensions, air density and air viscosity. The important effect of turbulent flow is to break down most of the layer of stagnant air which, in natural convection, functions as a thermal barrier

between the hot surface and the cooling air. The cooling effect of forced convection can be many times greater than that of natural convection even with moderate air-flow velocities but it decreases with altitude. It is proportional to air density to the power 0·8 and at 50,000 feet is therefore only $(0{\cdot}012/0{\cdot}08)^{0{\cdot}8}=0{\cdot}22$ times the effect at sea level. Thus as altitude is increased the temperature difference between the machine surface and the cooling air must also increase.

The absolute temperature of the machine would also increase in the same way were it not for the fact that up to about 30,000 feet the air temperature decreases with increasing altitude as was shown in Fig. 3.2. This temperature fall offsets to a considerable extent the decreased cooling effect arising from reduced density. At greater altitudes, where the air temperature is fairly constant, machine temperatures rise steadily with altitude and sometimes have to be restricted by derating machines for high-altitude operation. An example of this is the a.c. generator shown in Fig. 6.23 which is rated at 22·5 kVA up to 30,000 feet and 15 kVA from 30 to 50,000 feet.

Blast Cooling. Blast cooling, or ram air cooling, means cooling by an air supply which is obtained, while the aircraft is in flight, from a forward-facing scoop. This method is commonly used for aircraft generators and large equipments which require fairly large volumes of cooling air, sometimes as much as 200 cu. ft. per min. The velocity of the air supply depends primarily on the forward air speed of the aircraft and is practically independent of altitude. The temperature of the air is increased as it is collected by the scoop because it is compressed adiabatically, that is, without loss of heat. The adiabatic temperature rise, T, is given, approximately, by the formula

$$T=\frac{v^2}{10{,}000}\text{ Centigrade degrees} \qquad (13)$$

where v is the air speed in m.p.h. The final or stagnation temperature of the air, taking account of altitude and initial air temperature, is shown for a range of speed in Fig. 3.3. Since air density decreases with altitude, and air temperature increases with forward speed, blast cooling is limited by both these parameters. This is indicated by diagrams of the form shown in Fig. 5.11.

AIR FLOW THROUGH D.C. GENERATORS

In many early generators, such as those shown in Figs. 5.12 and 5.13, the cooling air was directed on to the working surface of the commutator and after passing round the commutator and over the brushgear was expelled at an outlet diametrically opposite the inlet. Such an arrangement did not cool the armature and field windings effectively and the demand for light weight and higher ratings brought arrangements which channelled the air from the commutator through the machine, to exits near the drive end. Some of these

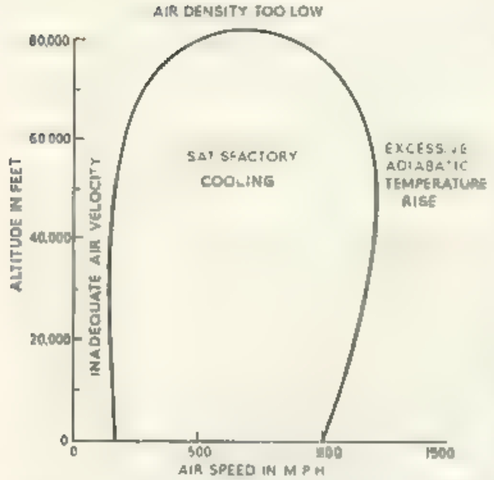


FIG. 5.11. *Typical altitude and forward-speed conditions for satisfactory blast cooling.*

arrangements used a jacket on the outside of the yoke, as shown in Fig. 9.14, and others passed the air between the field windings, and between the pole faces and armature surface. More elaborate still are designs such as that shown in Fig. 5.14 in which air is passed not only along the outside surface of the armature but also through the hollow shaft, entering at the commutator end and being expelled, assisted by centrifugal action, near the drive end.

The development of generators with interpoles and compensating windings brought generators with very restricted axial air passages. This

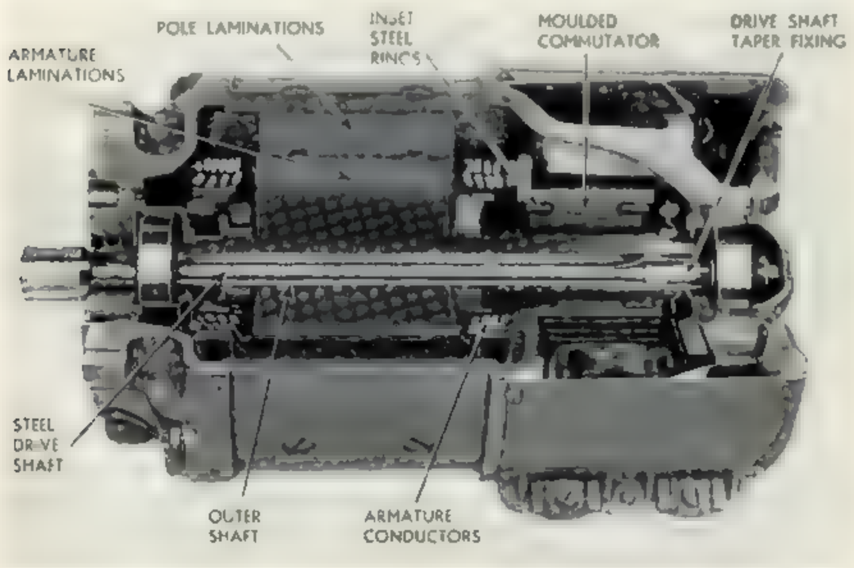


FIG. 5.12. *German generator of about 3 kW rating.*

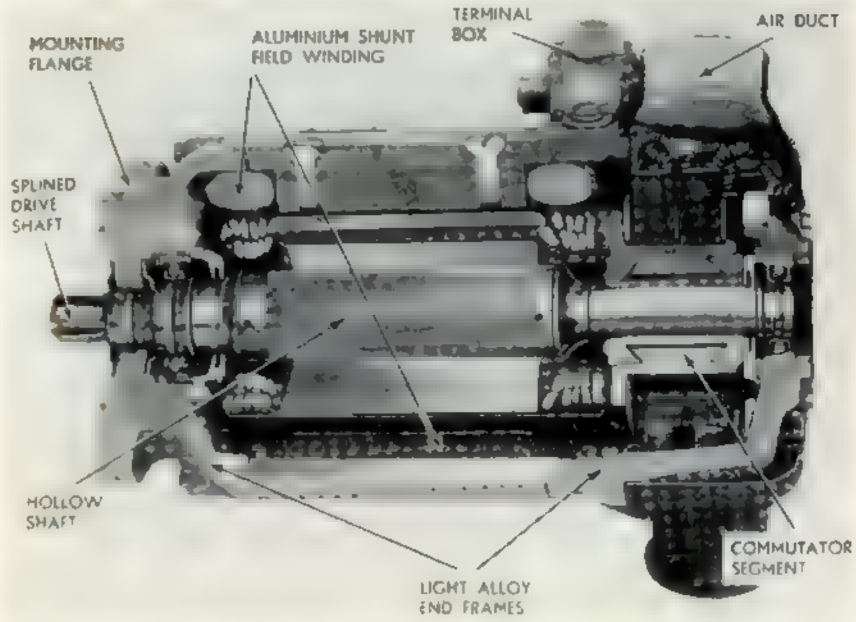


FIG. 5.13. *Bosch 30-volt, 3 kW generator, 6,000–8,000 r.p.m. Weight 38½ lb.*

trend has tended to raise the pressure head required to pass adequate air through the machines and modern designs show that attention has been given to reducing the resistance to air flow. The large air-inlet pipe, nearly 2 in. internal diameter, and the shaping of the end cover in Fig. 5.14 are examples of such design. Pressure heads are usually between 3 and 10 in. of water.

Air flow is ducted to generators through thin-walled pipes of 2 to 3 in. diameter. The outlets from generators are often required to be ducted to atmosphere and not allowed to spill into engine nascelles. Occasionally this has been because the nascelles are found to be slightly pressurized during flight, thus causing a restriction of the air flow. A second reason is that in the event of some generator failures, such as serious bearing failures, the generator is liable to overheat and present a fire risk. The ejection of sparks has been reported from the air outlets of generators running in such conditions.

COMMUTATORS AND BRUSHGEAR

In very early d.c. machines it is said that the rating was set by the limit of satisfactory commutation, but increased understanding of commutation

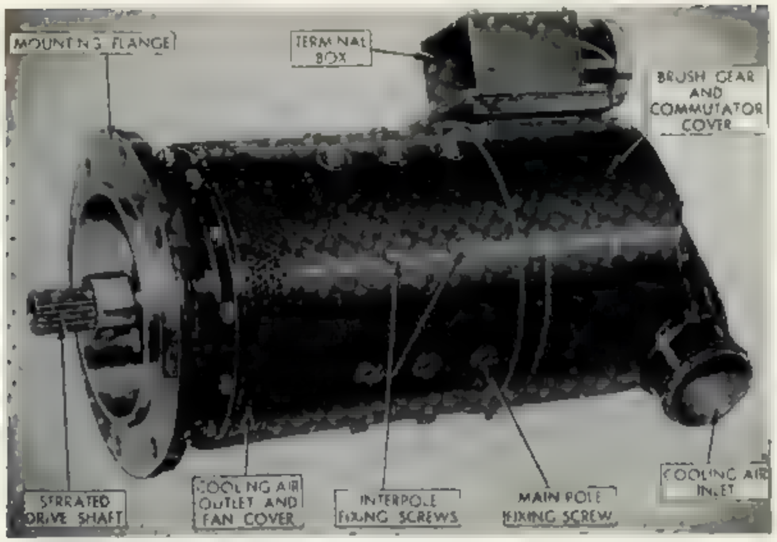


Fig. 5.14. *Rotax 6 kW d.c. generator weighing 42 lb.*

raised that limit until machine ratings were limited instead by temperature rise. The development of aircraft generators, with vastly improved methods of cooling, has brought the commutation limit again to the forefront. Many of the commutation problems which harrassed the early designers have been solved; particularly, it is now possible by the use of interpoles and compensating windings to establish the required magnetic field around the armature conductors undergoing commutation. However, the problem of constructing a commutator which will retain its shape to the necessary degree of accuracy under high speed and high temperature is still unsolved.

Most aircraft generator commutators are of fairly conventional construction as may be seen from Fig. 5.13, but special care is given to the processes of baking and tightening and to the final surface finish. Owing to the high stresses occurring in the bars at high speeds and to the loss of strength of pure copper at elevated temperatures, alloys of copper and silver, or copper and chromium are used. Even when all precautions have been taken, the highest practicable speed for commutators of the diameters usual for large aircraft generators, 3 to 4 in., is about 12,000 r.p.m. At higher speeds it has been found that commutators deform by becoming eccentric or by the lifting of one or more bars. This deformation is sometimes elusive because the commutator may reform when the speed is reduced. Deformation can be measured while the commutator is rotating by using a capacitance type pick-off.

An instrument for measuring the small capacitance changes caused by

commutator deformation is described in Ref. 2. It is believed that satisfactory commutation at high speed and heavy electrical load requires that the highest bar is not more than 0·0001 in. above the mean level and that the difference between maximum and minimum commutator radii is not greater than 0·0005 in.

An interesting example of the results of a high-speed, high-temperature commutator test is shown in Fig. 5.16. The segments are from a large commutator which, after successful operation at normal temperatures, failed by partial disintegration during a run at 200 deg. C. and at 11,500 r.p.m. Inspection of the segments shows that cracks developed at the riser ends which in some cases extended and opened sufficiently to allow the segments to leave the commutator under centrifugal force.

Although work on commutator construction continues it appears improbable that a commutator design, capable of operating satisfactorily under all required conditions, will be evolved. Recognition of this has given considerable impetus to the study of brushgear. One such study of aircraft generator brushgear, reported in Ref. 3, makes estimates of the maximum acceleration experienced by a brush on a very slightly distorted commutator. It deduces that the nature of the brush-to-commutator contact is probably one of continuous vibration, even under favourable conditions. A detailed consideration is also made of the forces acting on a brush in a holder and

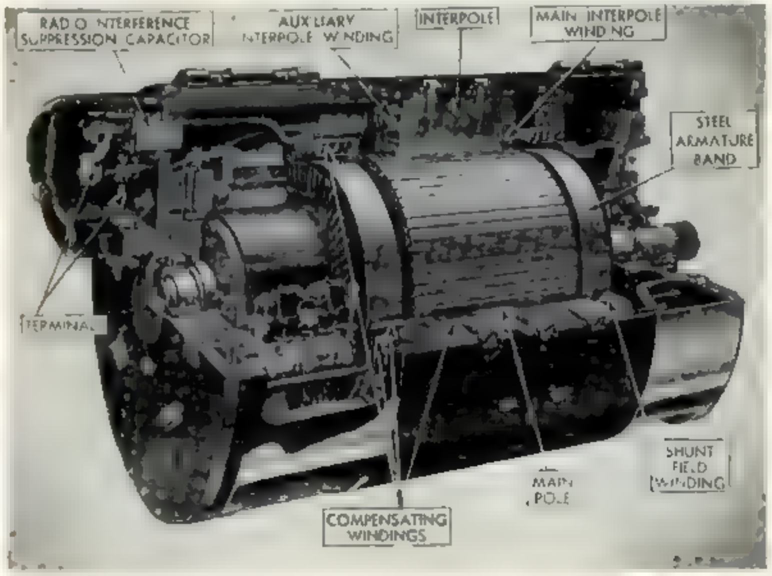


Fig. 5.15. *Rotax 22·5 kW, 112-volt wide-speed-range d.c. generator. Weight 138 lb.*

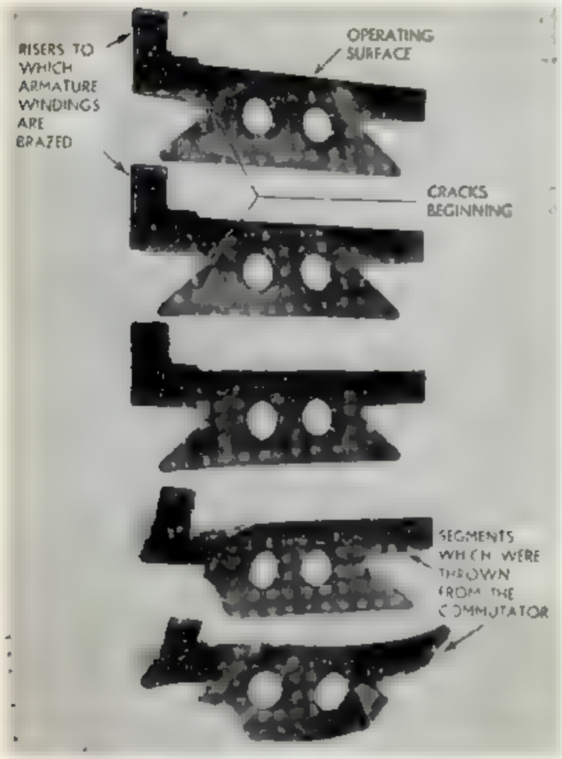


FIG. 5.16. *High-tensile copper-alloy commutator bars after overspeed test to destruction, illustrating pattern of ultimate failure.*

the causes and effects of changes of the coefficient of friction between the brush and the commutator surface, on the brush position and the centre of current collection under the brush. No precise practical conclusions are drawn, but the impression is given that the conventional brush, carried in a brush box, has a number of inherent features which will prevent the perfection of commutation.

COMMUTATION TESTS

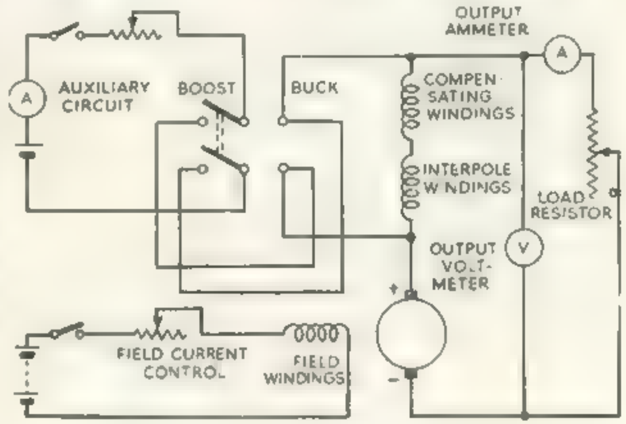
The simplest check on commutation is visual observation for sparking, and minimum sparking was the criterion by which the manually adjusted brushgear of early machines was positioned. More analytical tests have since been devised, some of which endeavour to show how the current in individual armature coils changes during the commutation process. Aircraft generators have been widely subjected to a test giving quantitive information about the spark-free commutation conditions. This test requires visual observation of the commutator and is termed the "black-band" test.

Black-band Test. This is normally applied only to generators having interpoles or interpoles and compensating windings, and is carried out using the circuit shown in Fig. 5.17. The procedure is to operate the generator at selected values of speed and load and at normal output voltage. The auxiliary circuit is then closed with the resistor at maximum and with the buck-boost switch in either position. Simultaneously, the output voltage and speed are maintained at the initial values and the auxiliary current is increased until sparking is just visible at the generator brushes. The value and

sense of the auxiliary current is recorded. This procedure is repeated with the sense of the auxiliary current reversed. A number of pairs of auxiliary current values are obtained for different values of output current and plotted as shown in Fig. 5.17. The curves represent boundary values of interpole- and compensating-winding current, above and below normal, within which sparking does not occur. The zone enclosed between the curves is called the black band.

The speed of the generator is a function of the torque/speed characteristic of the drive, and adjustments which may be made to maintain constant speed are of no significance to the test. Changes which are made to maintain constant output voltage are necessary because of redistribution of flux within the generator. Many aircraft generators require an adjustment of field current of up to ± 30 per cent when the auxiliary current is at a boundary value.

The practical difficulties of the test are the simultaneous observation of all the brush edges and the estimation of the auxiliary current setting at which sparking is just beginning. These difficulties may be alleviated to some extent by using a sensitive voltmeter or amplifier and cathode-ray oscilloscope to detect the noise voltages caused by sparking.



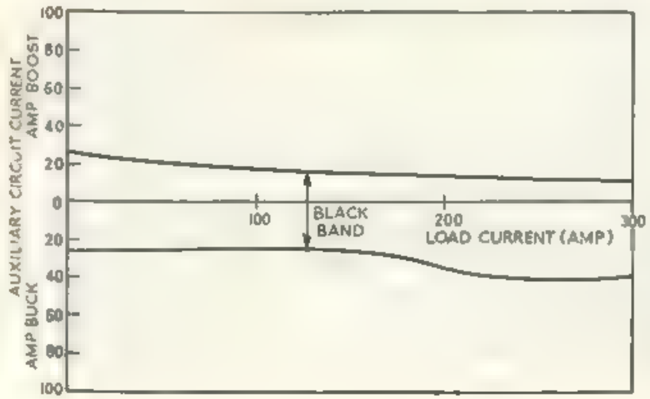


FIG. 5.17. (Above) *Circuit for black-band commutation test.* (Left) *Black band for a 9 kW generator operating at 8,000 r.p.m.*

BRUSH VOLT-DROP TEST

The small differences of mean potential between points on the commutator surface underneath a brush, and the brush holder, give an indication of the current density existing at various points on the brush-commutator interface. This test has been used extensively on industrial machines having a number of brushes connected in parallel and positioned along the length of the commutator. For such machines, one of the brushes is replaced with an insulating block, drilled with holes to receive a small-diameter probe by means of which the interface potentials may be measured. Since the commutator bars are of very low resistance and are aligned along the axis of the machine, this arrangement gives similar results to those which would be obtained if the probe were positioned at a real brush-commutator interface. If the probe voltages are plotted against the position of the probe around the commutator surface, as shown in Fig. 5.18, a shape of curve is obtained which is characteristic of the way in which commutation is being effected.

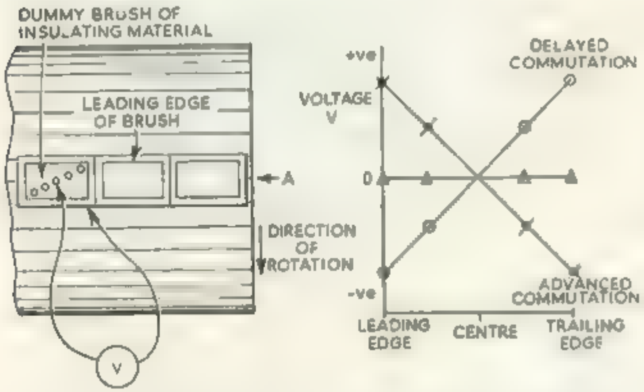


FIG. 5.18. *Diagram of brush volt-drop commutation test, and method of presenting results.*

In aircraft generators the number of brushes at any one brush position does not normally exceed two, and the current density at the brush surface is designed to be as high as possible. Thus it is not practicable to fit a dummy brush. Also the space round the commutator is very densely packed with brushgear and connexions, and sometimes with such items as equalizer dropping resistors, so that it is a matter of some difficulty to carry out this test. Sensible results have been obtained by reducing the axial length of a brush and fitting a small insulating block having only three probe positions. Another artifice which has been used is to arrange for the probes to bear on the end faces of the commutator segments, as indicated by the arrow *A* in Fig. 5.18, but this is not usually possible without modification to the generator end frame and brushgear fixings. Further details of this test are given in Refs. 4 and 5.

EXCESSIVE BRUSH WEAR AT HIGH ALTITUDES

This effect was first experienced early in the second world war when reconnaissance aircraft began to fly regularly, and for periods of more than one hour at altitudes above 20,000 feet. Carbon brushes, which under normal circumstances would have lasted for several hundred hours, were found to wear away in one or two hours. The dust was drawn through the machine by the cooling air, and it was often necessary to dismantle and clean the generator, as well as replace the brushes, before returning it to service.

The onset of excessive wear begins some time after the generator has entered a low-pressure, low-humidity atmosphere, and is marked by the breaking up of a film which forms on the commutator surface during normal operation. The onset of excessive wear is accelerated by high temperature or sparking, and it is almost certain that many of the early cases reported as high-altitude brush wear were actually caused by these things as much as by altitude. The principal remedy for high-altitude wear is the use of impregnated or cored brushes, which carry a material capable of forming a film to replace the natural commutator film. Lead, barium fluoride and poly-tetra-fluoro-ethylene have been used as impregnants with some success. Brushes with molybdenum-disulphide cores appear to be even more successful. The cores are several in number and lie along the length of the brush, opening on to the wearing surface.

Unfortunately, although high-altitude brushes undoubtedly have superior performance at high altitudes, their performance and life under normal conditions is invariably inferior, necessitating lower current densities and better commutating conditions. A recent approach to the problem is the use of cadmium-plated commutators.

RADIO INTERFERENCE SUPPRESSION

Sparking at brushes is a visual indication of current fluctuations, some of which occur at very high frequencies and spread over a wide frequency band. Even in generators having "black" commutation some high-frequency fluctuations occur and will, if unchecked, give rise to interference on nearly all radio and communication circuits, either by radiation or by direct conduction through the aircraft power cables. It is therefore necessary to provide a high-frequency filter as near as possible to the brushgear, and screening for any lengths of cable between the brushgear and the filter. For early d.c. generators the filters were simple inductance-capacitance filters fitted externally in the output cables and field cable, and connected to the generator by a length of cable screened with tinned copper braid. Since the inductors in the output cables were required to carry the full generator output current they were heavy. Present practice is to use the series windings of the generator as the filter inductors and to build the necessary capacitors inside the generator

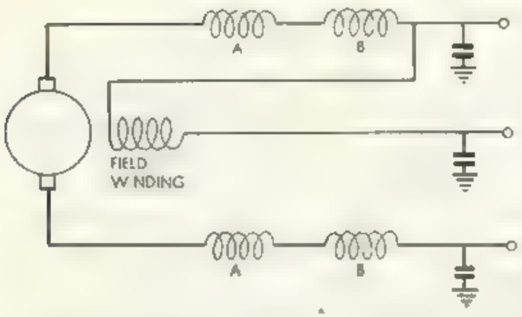


FIG. 5.19. *How the stator windings of d.c. generators are used as radio-interference-suppressor inductors. Half the interpole windings are indicated by* A, *and half the compensating windings by* B.

frame, thereby simplifying the installation and saving weight. Fig. 5.19 illustrates this arrangement and Fig. 5.15 shows a generator with built-in capacitors.

DRIVES AND MOUNTINGS

The advantages to be derived from the operation of d.c. generators at constant, or nearly constant speed, follow from the discussions earlier in this chapter on generators and regulators, but at present the provisions of such drives incurs penalties of complexity and weight which are out of proportion to the advantages gained. Almost invariably, therefore, the main d.c. generators of an aircraft are directly connected through a fixed-ratio gearbox to the main engines. For minimum generator weight the ratio should be chosen so that the maximum rated generator speed coincides with the maximum engine speed. Other considerations, such as inferior commutation at the highest speeds, may make it preferable to choose the ratio so that at the engine cruising speed the generator is operating substantially below its maximum speed. In practice the gearbox is often built-in to the engine casing and the ratio may be predetermined by the engine designer in order to suit a number of different types of generators. The choice may also be influenced by the fact that the gearbox usually provides drives for other accessories, such as hydraulic pumps and fuel pumps. Generator speeds are between two and four times engine speed for piston engines, and a little less than the speeds of gas-turbine engines.

Generator shafts are usually extended for between one and two inches outside the driven end bearing and the extension is serrated, as shown in Fig. 5.14, to receive the drive. Splined extensions were used on early British and German designs, but serrations are now generally used. Most designs have used shaft extensions which are integral with the main shaft, but some U.S.A. and German designs have used quill shafts. These are effectively self-aligning and are also capable of absorbing driving-torque fluctuations. One such shaft is shown in Fig. 5.12. It necessitates a relatively large overall shaft diameter and drive-end bearing. Some U.S.A. designs also incorporated a friction damper within the hollow shaft to reduce the amplitude of torsional oscillation at the natural frequency. This is determined by the

inertia of the rotor and the torsional stiffness of the quill shaft and is likely to be between 20 and 30 cycles a second.

To ensure precise alignment between the generator shaft and the driving member, the drive end frame is provided with a spigot. The driving member, which is usually part of the engine auxiliary gearbox, is carried on its own bearings and thus imposes no side thrust on the generator bearings. Owing to the proximity of the generator drive-end bearing to the engine, this bearing is sometimes designed for oil lubrication from the main engine lubrication system, but in most generators both bearings are grease lubricated.

Generators of less than about 6 kW rating are carried by means of a flange, integral with the drive end frame, which is secured on studs mounted in the gearbox casing. The flange may be provided with a number of equally spaced holes permitting the generator to be mounted in a number of different positions. This method has presented difficulty when it has been necessary to design a large generator for a small flange mounting, and has given rise to generators having a pronounced "neck" between the flange and the body, such as may be seen in Fig. 5.14. It is to be expected that a neck of adequate structural strength would be heavy and also that a generator mounted in this fashion would have a fairly low natural frequency of vibration. If this should coincide with a frequency of vibration set up by the engines, as discussed in Chapter 3, large amplitudes of movement may be expected at the unsupported end, and large stresses may be set up in the material at the neck. Larger generators, such as the one shown in Fig. 5.15, are cradle-mounted. This method permits a weight saving at the generator end frame and reduces the amplitude of vibration which is likely to be experienced at the commutator or non-drive end.

SERVICING

Generator servicing is arranged to coincide with the aircraft checks discussed in Chapter 2 under the heading *Life*. The details of generator servicing carried out at each check will depend very much on the experience acquired in operation, since it has been found that generator life is very dependent on the aircraft in which the generator is installed. Identical generators have operated for more than twice as long, between major overhauls, in some aircraft than in others. The generator servicing which may be expected at the least comprehensive aircraft checks is more in the nature of inspection. On removing the generator air pipes and window straps, the condition of the interior would be examined carefully before cleaning or disturbing the parts in any way. The presence of carbon dust would be accepted as normal. Signs of oil, copper dust or corrosion, or discoloration indicating overheating would necessitate investigation, either of the generator or of its associated equipment.

The value of this careful examination before cleaning cannot be overstressed. Brushes might be checked for freedom of movement in their boxes, and for length, sufficient length being required for operation until the next check. Brush-spring tensions might be checked by a spring balance. The commutator surface would probably be cleaned with benzine but generally not with an abrasive. Burns, pitting or scoring would be causes for overhauling the generator. A check on the tightness and locking of accessible nuts and screws might be made.

At some of the more comprehensive aircraft checks generators would be removed for overhaul. This entails dismantling to the extent of removing brushes and brushgear, end frames and armature. It is undesirable to remove the poles from the yoke if the pole faces have been ground after assembly. After cleaning, the armature windings can be checked for resistance and insulation to the shaft. The commutator can be checked for eccentricity and bar-to-bar irregularities, and skimmed if necessary, provided the final diameter is greater than the specified minimum value. Field windings, including interpole and compensating windings, can also be checked for resistance and insulation. Bearings can be checked for roughness and wear, and repacked with grease before reassembly. Oil seals can be replaced if necessary. If new brushes are fitted they are bedded, initially by the use of an abrasive tool which forms the brush surface to approximately the correct radius, and finally by running the machine, partially loaded, for as long as may be necessary. In high-performance generators, where 100 per cent contact is required, the final bedding may take many hours.

Testing after overhaul is usually carried out on a bench test rig where the generator can be driven at a controlled and measured speed, cooled and electrically loaded. It may include winding-resistance checks, measuring from the machine terminals, and insulation-resistance checks on hot windings. If a new armature has been fitted, an over-speed test may be required with a subsequent recheck of commutator dimensions. The vibration level during the over-speed run is an indication of the fineness or otherwise of armature balancing. A commutation test, such as the black-band test described earlier, may be carried out, and from the results of this test the final setting of brush positions round the commutator may be made. A heat run may be carried out to determine temperature rises after a period of operation at about full load. The mean winding temperatures are generally determined by using equation (6) rearranged as follows

$$T_2 = T_1 + \frac{r_2 - r_1}{\alpha r_1} \text{ deg. C.} \qquad (14)$$

A check is usually made on the value of field current required for certain load and speed combinations. This confirms the correctness of windings and connexions, the properties of the iron and the length of the air gap.

CHAPTER 6

Power Sources: A.C. Generators

THE first a.c. generators to be used in large numbers were of the inductor type and were installed to provide power for the radar equipment used in the bombers of the second world war. These were auxiliary generators in the sense that they were not part of the main aircraft power system, but were used to provide power for a few particular items of electronic equipment. Inductor generators were selected because they are naturally suited for the frequency range, 1,000 to 2,000 c/s, which was considered to be ideal for the equipment. There are, however, other equipments for which a much lower frequency is desirable, and the requirement for frequencies in the range 250 to 650 c/s resulted in the introduction of salient-pole, rotating-field generators. These have now practically superseded inductor generators.

The salient-pole generators are of two kinds, those designed for operation over a wide speed range and those designed for constant-speed operation. The former have sometimes been used as auxiliary generators, but in many aircraft they have been used to provide all the electrical power, partly as variable-frequency a.c. and partly, after rectification, as d.c. The latter are mostly of fairly recent design and are used as the main generators in aircraft having constant-frequency systems.

The introduction of constant-speed generators was always recognized as desirable, because variable-frequency power is suitable only for a limited number of applications and also because generators operating at different frequencies cannot be connected in parallel; it was delayed, however, because of the difficulty of obtaining a constant-speed drive. Many attempts have been made to build a unit, which when driven from the main aircraft engines, would in turn drive a generator at constant speed, but only since about 1950 have satisfactory units become available. Small gas turbines and air turbines, operating at constant speed, have also become available in the past few years and constant-speed generators have been designed to suit these drives. Nearly all constant-speed generators operate at 400 c/s, the frequency now universally accepted as standard for constant-frequency aircraft systems. It is a compromise between the optimum frequencies for light-weight electronic

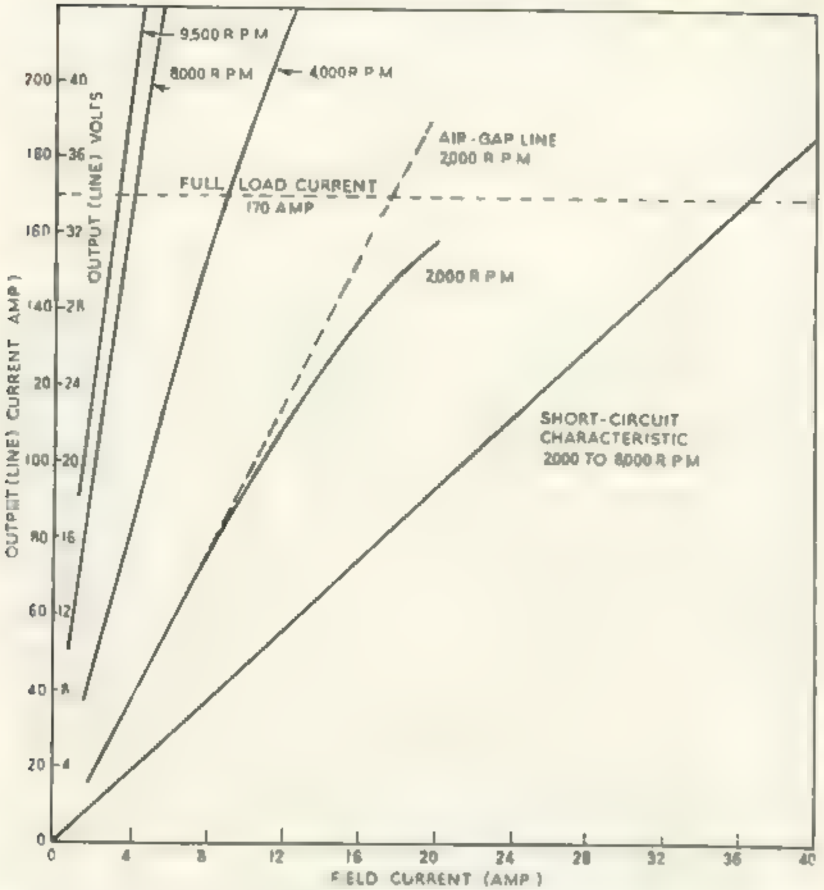


FIG. 6.1. *Open- and short-circuit characteristics for a Rotax 8 kVA three-phase a.c. generator.*

equipment and light-weight rotating machines. Other types of a.c. generators, such as induction generators, are the subject of present studies but the prospects of immediate applications are not very good.

SALIENT-POLE, ROTATING-FIELD GENERATORS

Open- and Short-circuit Characteristics. Some aspects of the performance of a.c. generators may be assessed from their open- and short-circuit characteristics. These also provide a convenient means of comparing the aircraft machines with those built for other applications. Fig. 6.1. shows the characteristics of an 8 kVA generator designed for wide-speed-range operation. From these curves it may be seen that the value of the synchronous impedance

of this generator depends on the operating speed. The British Standard for Aircraft A.C. Generators (G.124) defines per-unit synchronous impedance as the ratio of short-circuit excitation for full-load current to open-circuit excitation for normal voltage, the latter being determined from the air-gap line. Using this definition it will be found that the synchronous impedance of this generator is 2·6 per unit at 2,000 r.p.m. and 14 per unit at 9,500 r.p.m.

As no particular speed within the operating range of a wide-speed-range generator may be described as synchronous, the meaning of the term *synchronous impedance* is open to question. It is useful, however, to retain the term, understanding that it means operating impedance and to qualify it with the speed. The values of synchronous impedance of this machine, even at the lowest speed, are high compared with the values for conventional machines. The practical consequences of such high values are, firstly, that the inherent regulation of the generator is very high. It follows that the field current of the generator must be controlled over a wide range of values if the output voltage is to be maintained constant under all operating conditions. This generator, running at 6,000 r.p.m., requires only 4·7 amp. field current at no-load and 38·4 amp. at full-load, unity power-factor.

The second consequence of high synchronous impedance is that the instantaneous value of current which the generator can deliver to a short-circuit fault is very small. This simplifies the design of circuit-breaker contacts and arc-extinguishing devices but proves to be an embarrassment if the generator is used with protective devices which require substantial fault current for their operation. B.S. G.124 recommends that the synchronous impedance of constant-speed generators should be less than 2 per unit. In order to achieve this relatively low value the air gaps of some machines have been made longer than the optimum for a minimum-weight machine.

The open-circuit curves of Fig. 6.1 show that voltages very much in excess of the rated generator voltage can be developed at higher speeds. In this respect a.c. generators resemble d.c. generators and over-voltage protection is equally necessary. The short-circuit curve shows that the current available is unaffected by speed and that the highest value is only a little greater than full load. In this respect a.c. generators differ radically from d.c. generators; this difference arises because the d.c. generator has no counterpart of synchronous reactance, the principal component of synchronous impedance.

Load Characteristics. Curves relating the field current required to maintain constant voltage and the output current are shown in Fig. 6.2. These confirm the preceding statement on the wide range of field current required with changing output current. They also show two characteristics which permit a useful modification to the duty of the voltage regulator. The first is

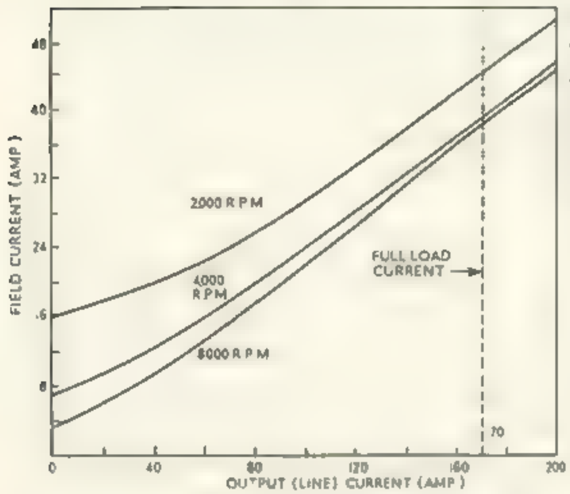


FIG. 6.2. *Curves for a Rotax 8 kVA three-phase a.c. generator relating output (line) current and field current at various speeds. Output (line) voltage is constant at 27·6 volts, and employing a strip winding.*

that, at any speed, the field current is approximately proportional to output current over most of the load current range. Secondly, changes of speed have only a small effect on the field current required except when the output current is very small. From Fig. 6.2, it can be seen that, at full load, doubling the speed from 2,000 to 4,000 r.p.m. requires a reduction of field current of less than one-eighth, from 44 to 38·7 amp., whereas at no-load the same speed increase requires a reduction of a little more than half, from 15·7 to 6·9 amp. The application of these characteristics is discussed in Chapter 11.

These characteristics may be confirmed from the study of a voltage diagram for a generator having high synchronous impedance. This is shown in Fig. 6.3. The synchronous reactance volt drop, Ix_s, is approximately in phase with the generated e.m.f., e, and to maintain constant terminal voltage, V, any change in the magnitude of the output current, I, and hence of the re-

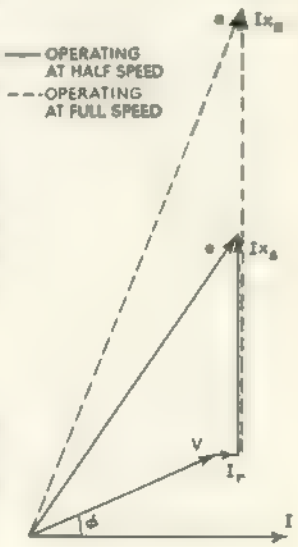
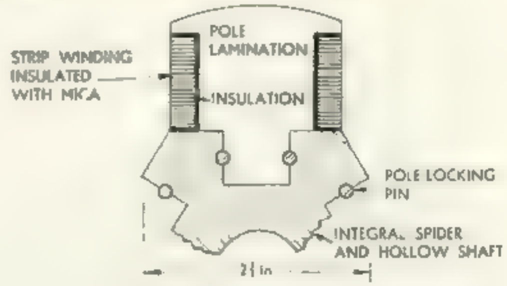


FIG. 6.3. *Voltage diagram for an a.c. generator with high synchronous reactance:* I *is the output current;* V *is the terminal voltage;* ϕ *is load power-factor angle (approximately 0·9 lagging);* r *is armature resistance;* x_s *is synchronous reactance;* e *is generated e.m.f.*

FIG. 6.4. *Cross-sectional diagram of an a.c. generator rotor pole, employing a strip winding.*



actance volt drop, Ix_s, requires a corresponding change of e. Except when the magnetic circuit is approaching saturation, e is approximately proportional to field current. Thus a change of output current requires a nearly proportional change of field current. By drawing diagrams for several values of synchronous reactance, x_s, it can be seen that the proportionality is improved as x_s is increased. Changes of speed cause similar changes of e and x_s, and since e and Ix_s are of similar magnitude and nearly in phase, only a small adjustment of field current is necessary to maintain constant output voltage.

The high values of field current required by this generator at full load, 38 to 44 amp., arise partly because of the field-winding construction. In order to obtain a winding which is secure against centrifugal force, strip copper is wound on edge around the pole shank as indicated in Fig. 6.4. It is difficult to wind strip in this manner if the thickness is less than about one-fifteenth of the width, consequently such windings have only a small number of turns and the necessary m.m.f. (ampere-turns) can only be obtained by using large currents. Some generators have wire-wound rotors but these usually operate at no more than 8,000 r.p.m. and are fitted with winding retainers between the poles.

Fig. 6.5 shows how the efficiency of the 8 kVA generator changes with output, and indicates how the losses increase with speed. Windage and friction losses increase about ten times with a speed increase from 3,000 to

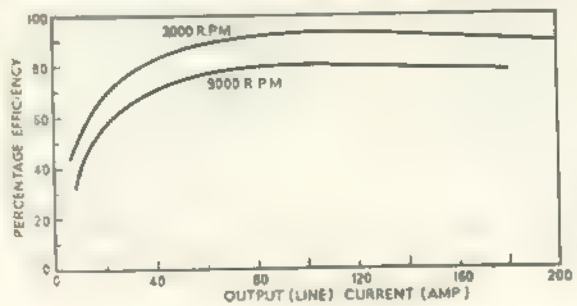


FIG. 6.5. *Curves for Rotax 8 kVA three-phase generator relating efficiency and output current.*

9,000 r.p.m. Losses arising from eddy currents in the stator conductors also increase very rapidly and these two losses account for most of the difference between the two curves.

Constant-speed generators are similar to variable-speed generators but their design is simplified since the quantities dependent on speed, such as frequency, reactance values, eddy-current losses in iron and copper, hysteresis losses and excitation current, are either constant or restricted to a smaller range. These generators are usually intended for parallel operation and are provided with damper windings in the pole faces to minimize hunting, or swinging of the rotors about their mean synchronous position.

The effects of load power-factor are the same on aircraft generators as on conventional generators but are accentuated by the high values of synchronous reactance. Lagging-power-factor loads have a demagnetizing effect which must be offset by extra field m.m.f. in order to maintain constant output voltage. Since there is a limit to the current rating of field windings it is usual for manufacturers to specify the lowest lagging power-factor at which a generator is capable of delivering its rated output. This is rarely lower than 0·75. Leading-power-factor loads are possible but are not normally met. Such loads, if sufficiently leading, have a magnetizing effect. The correction of load power-factor is not generally necessary in aircraft but can be achieved by the addition of capacitors in parallel with the load. These effects may be confirmed by redrawing the voltage diagram, shown in Fig. 6.3, for different values of power-factor angle, ϕ.

EXCITATION AND VOLTAGE REGULATION

Self-excitation. The excitation of a.c. generators has presented many more problems in aircraft than has the excitation of d.c. generators; a number of methods are used, some involving one or two additional machines functioning as exciters. Self-excitation, as commonly used for d.c. generators, can be arranged for a.c. generators but it is necessary to rectify some of the generator output before feeding it to the field winding, as shown in Fig. 6.6 (*a*). Self-excitation is less certain than with d.c. generators, firstly because the iron laminations used for parts of the field magnets have a lower remanence, or residual magnetism, than the steels used for d.c. generators, and secondly, because the rectifiers have high forward resistances when subjected to small voltages. Certainty of excitation can be secured by building small permanent magnets into the generator field system or by making provision for field "tickling". This is the practice of momentarily connecting a d.c. supply to the field windings.

Most variable-speed a.c. generators used in rectified a.c. systems are self-excited but depend on the aircraft accumulator for initial excitation. It cannot be overlooked that any generator which depends on external

equipment or supplies for its excitation is a greater risk than one which is inherently self-exciting. To achieve satisfactory reliability from such a generator, methods must be devised to ensure that re-excitation is possible regardless of other circumstances, such as may be occasioned by a partially discharged accumulator.

Built-in Exciters. Partial independence of external supplies and relief from the problem of controlling the relatively large excitation current discussed under the headings *Open- and Short-circuit Characteristics* and *Load Characteristics*, can be achieved by using a d.c. exciter. These are invariably built in a common frame with the a.c. generator and bring with them all the problems associated with d.c. generators, although most of them are favourably modified. Owing to the small size of the exciter it is practicable to design a little more generously than for main d.c. generators. This, together with the small commutator diameter, helps to secure satisfactory commutation. Built-in exciters are mostly used on constant-speed a.c. generators and their design is simplified by the advantage of constant-speed operation.

Voltage regulation of the a.c. generator by control of the d.c. exciter field current is attractive because of the relatively low value of the field current. The inductance of the exciter field winding unfortunately increases the response time of the system and delays the return of the a.c. output voltage to normal after changes of load. Overloads and faults on the a.c. lines have been known to cause loss or reversal of the residual magnetism of the exciter. This is because large changes of the a.c. generator output, or armature current, cause large changes of armature reaction flux; these induce currents in the circuit formed by the a.c. generator field and the exciter armature, and armature reaction in the exciter demagnetizes its field. Because of this, an external d.c. supply is still required for re-excitation after faults.

Alternating current exciters are practicable but their output must be

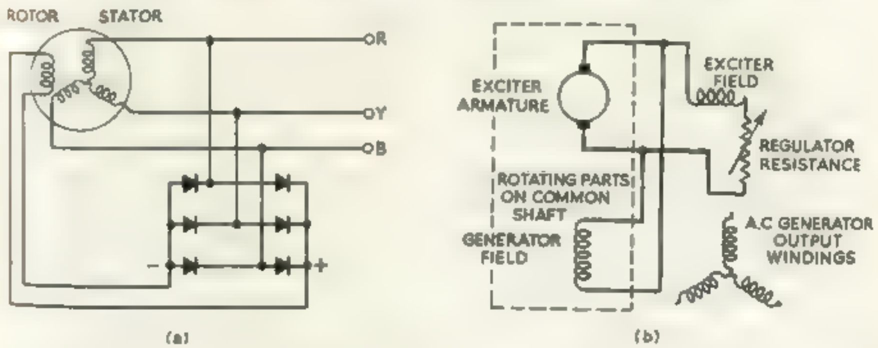


Fig. 6.6. (a) *Circuit for self-excitation of an a.c. generator.* (b) *Schematic diagram of an a.c. generator with d.c. exciter.*

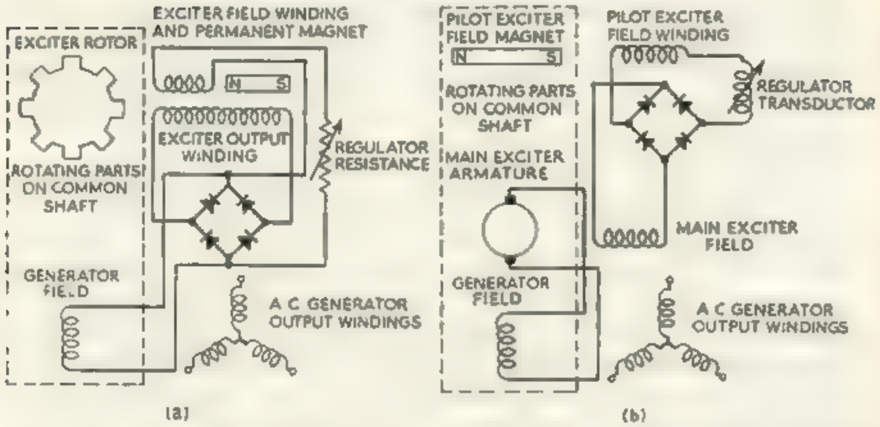


FIG. 6.7. *Schematic diagrams of an a.c. generator* (a) *with inductor generator exciter;* (b) *with pilot and main exciters and transductor voltage regulator.*

rectified before being passed to the a.c. generator field. In some cases these have the same problem of initial excitation as with main a.c. generators but they have the advantages of being smaller and more rugged than d.c. exciters. Since the exciter frequency is relatively unimportant, inductor generators, which are described later (see *Inductor Generators* page 88), are sometimes preferred because they are brush-less. A special case of built-in a.c. exciters is the rotating-rectifier machine to be described under the heading *Special A.C. Generators*. Figs. 6.6 (*b*) and 6.7 (*a*) show possible arrangements of d.c. and a.c. exciters.

Pilot Exciters. This is the name given to machines which excite the exciters of a.c. generators. Their primary purpose is usually to make the a.c. generator completely independent of external supplies both for initial excitation and for recovery after faults. An a.c. generator with a permanent-magnet rotating field is a logical choice for this function. The output of such a pilot exciter, which is also the main exciter field current, can be controlled either before or after rectification. The latter method would require a variable-resistance type of regulator, which could be one employing a carbon pile. Control of the pilot-exciter output before rectification can be effected by a transductor, which is a variable inductor as described later (*see Transductors*), and since the pilot-exciter frequency is unimportant, it can be chosen to suit a light-weight, quick-response transductor. Frequencies between 1,000 and 2,000 c/s are suitable, and a permanent-magnet generator using the Lundell type of construction, shown in Fig. 6.8, is a practical choice for a pilot exciter. Fig. 6.7 (*b*) indicates a possible method of connexion for an a.c. generator with a pilot exciter.

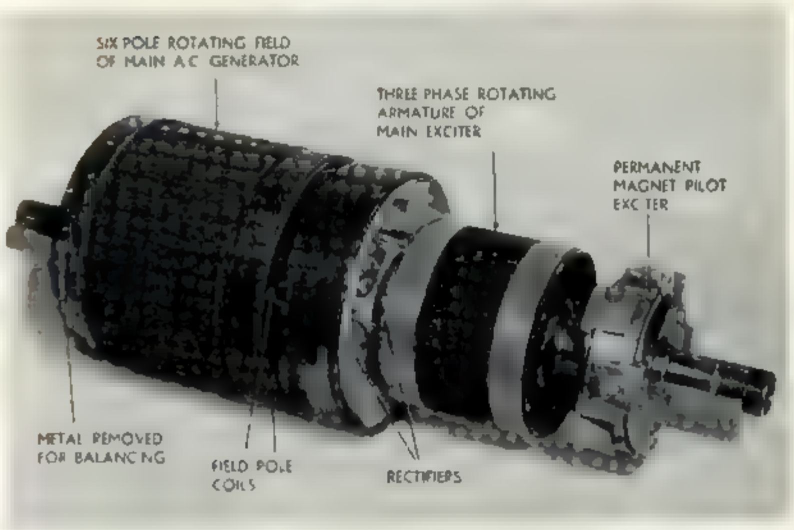


FIG. 6.8. *Rotor of a 40 kVA generator similar to the one shown in Figs.* 6.18 *and* 6.19. *The machine has a permanent-magnet a.c. pilot exciter using the Lundell type of construction, and an a.c. main exciter with rotating armature and rotating rectifiers to rectify the exciter output for the field of the main generator.*

Permanent-magnet pilot exciters may also be used as a source of power for protective equipment provided they are designed to give approximately constant voltage over the range of current demanded by the main exciter. This application is discussed in Chapter 10.

Synchronous Booster. This is an addition to some wide-speed-range generators which provide two or more independent outputs. To secure

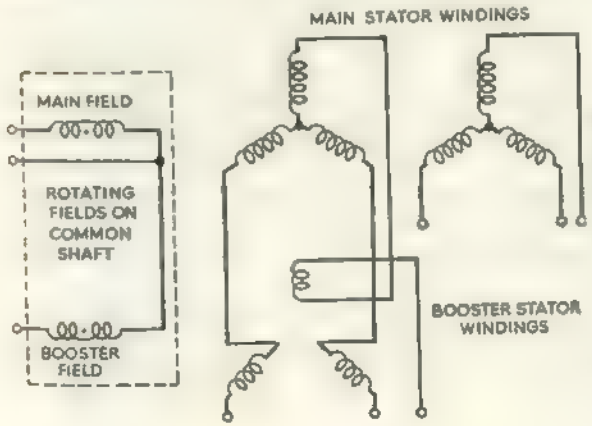


FIG. 6.9. *Schematic diagram of an a.c. generator having two electrically separate output windings, one of which is connected in series with booster windings for voltage regulation. The common field connexion reduces the number of slip rings from four to three.*

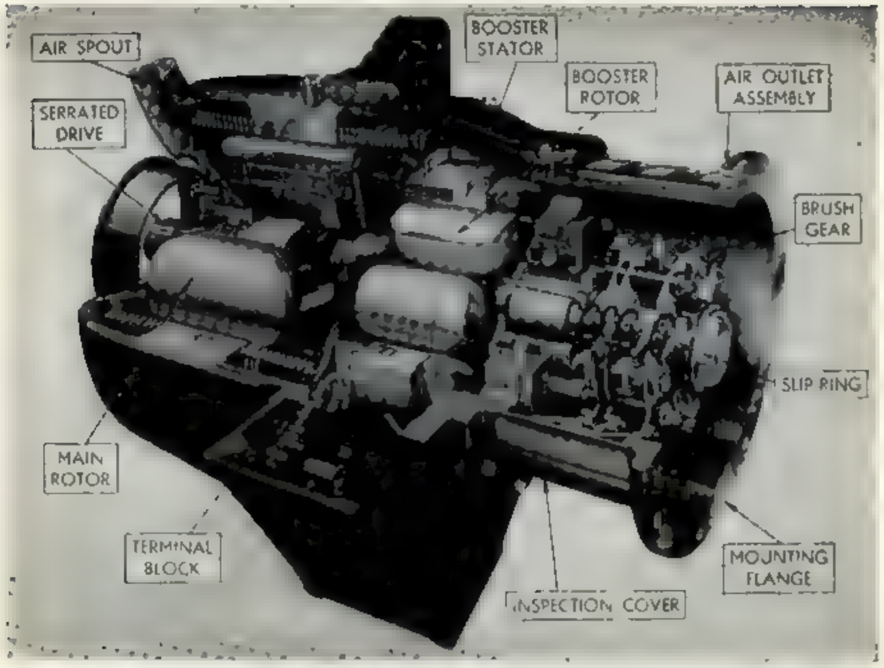


FIG. 6.10. *Sectioned view of a 50 kVA generator having two main stator windings, one of which is connected in series with synchronous booster windings. The longitudinal section of a main rotor pole may be compared with Fig.* 6.4.

control of two output voltages an auxiliary generator is used which is built on the same shaft as the main generator. This generates an e.m.f. in synchronism with those of the main windings, which can be added to the e.m.f. of one of the main windings by connecting the main and auxiliary windings in series, as shown in Fig. 6.9. The auxiliary generator is phased so that its output boosts that of the main winding, and it is described as a synchronous booster. Adjustment of the main field current controls all output voltages together, and adjustment of the booster field current controls the selected output independently. Thus two outputs can be regulated to a predetermined voltage. A method of controlling other outputs independently by using external equipment is described in Chapter 11 (see *Regulation of Multiple Outlets*).

A sectional view of an a.c. generator having a synchronous booster is shown in Fig. 6.10. This machine probably represents the most developed form of wide-speed-range generator for rectified a.c. systems and was initially used on the Bristol "Britannias".

VOLTAGE REGULATORS

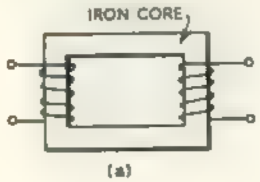
Carbon-pile Regulators. These regulators are essentially the same for a.c. generators as for d.c. generators but, owing to the higher field currents of some a.c. generators, attention has been directed to developing carbon piles capable of greater heat dissipation. The greater power-handling capacity has been achieved in some regulators by using several piles in parallel assembled in one regulator. Sealed piles are also being developed which should permit higher pile operating temperatures without deterioration.

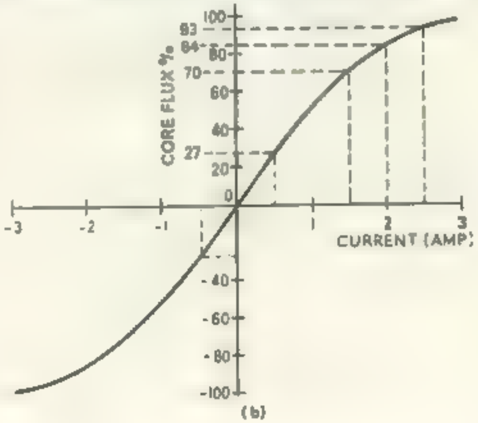
It is believed that there is no advantage in using the pile to control alternating instead of direct current but this alternative does not normally arise in practice because, in those installations where the a.c. generator field supply is obtained by rectification, the a.c. supply is usually three-phase. The voltage sensing coil, and any other coils on the regulator magnet, are invariably supplied with direct current obtained by rectifying the appropriate a.c. quantity. Despite the difficulties in the design and operation of carbon-pile regulators, they have, to date, been used for the majority of a.c. generators.

Transductors. Transductors, also known as saturable reactors, are essentially variable inductors in which changes of inductance are effected by changes of d.c. control current. In an a.c. circuit they offer a means of controlling current without incurring i^2r losses, except those which arise from the resistance of the transductor windings. Transductors are particularly attractive because they are free from moving parts.

Inductance may be defined as "flux linkages per ampere". With this definition in mind it will be appreciated that the inductance of an iron-cored coil decreases as the iron approaches saturation, since changes of current can then cause only small changes of flux. This effect is put to use in the following way. Consider an iron core having two windings of equal turns, represented in Fig. 6.11 (*a*), for which Fig. 6.11 (*b*) is a curve relating core

FIG. 6.11. (a) *A simple transductor with windings having an equal number of turns.* (b) *Curve relating core flux and winding current for the transductor shown in* (a).





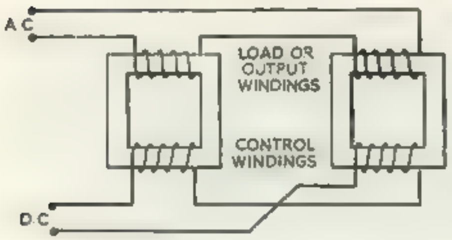


FIG. 6.12. *Twin-core transductor. The voltages induced in the control windings by the output current are in opposition.*

flux and current in either winding. From Fig. 6.11 (*b*), the core-flux change for a current change of one ampere from $-\frac{1}{2}$ to $+\frac{1}{2}$, in either winding, is ± 27 per cent of the flux when the core is highly saturated. Now, if a bias current of 2 amp. is passed through one winding, which will be called the control winding, the same change of current, $\pm\frac{1}{2}$amp., in the other winding causes a flux change of only +9 to −14 per cent. Thus the flux change per ampere, and hence the flux linkages per ampere, or inductance of the second winding, depends on the control-winding current. This winding will be called the load or output winding and the complete device is termed a transductor or saturable reactor.

Modification to this simple arrangement is necessary in practice because transformer action will cause induced voltages in the control winding when an alternating current is passed through the output winding. One method of counteracting this effect is the use of a second core, as shown in Fig. 6.12, so that the voltages induced in the control windings are in opposition. This arrangement is known as a twin-core transductor. For simplicity, only single cores are shown in subsequent diagrams.

The transductor permits an a.c. circuit to be controlled by a d.c. current and, if the winding ratio is appropriately chosen, a large a.c. current may be controlled by a small d.c. current. It is therefore likely to be one of the principal components of a voltage regulator for an a.c. generator which operates by controlling the output of an a.c. exciter, as mentioned earlier (see under *Excitation and Voltage Regulation*).

Transductor Voltage Regulator. Fig. 6.7 (*b*) shows a schematic dia-

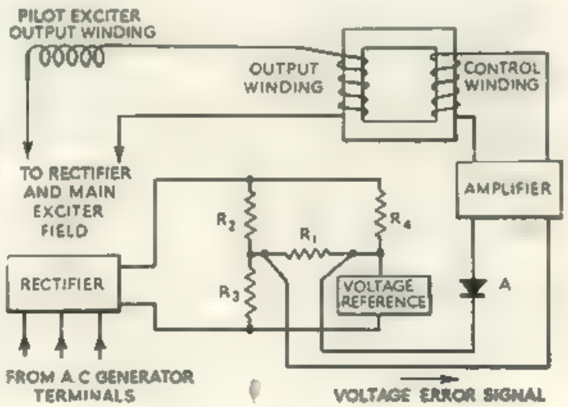


FIG. 6.13. *Transductor voltage regulator for the scheme shown in Fig.* 6.7 (b).

gram of an a.c. generator with an a.c. pilot exciter, the output of which is transductor-controlled. A simple scheme for the control circuit of this transductor is shown in Fig. 6.13. Unlike the carbon-pile regulator, this transductor regulator requires an external reference voltage and a means of comparing the generated voltage with the reference voltage. It may also require an amplifier to amplify the voltage error signal, which is derived from the comparing circuit, to a power level at which it can control the transductor. In the carbon-pile regulator the spring force serves as a reference, the comparison is effected mechanically and the regulator is inherently sensitive because small pile-force changes cause large pile-resistance changes.

In Fig. 6.13 a voltage proportional to the difference between the generator output voltage and the required voltage appears across the resistor R_1, and the voltage error signal, after amplification, is passed to the transductor control winding. The resistors R_1 to R_4 and the reference voltage are chosen so that at normal voltage the error signal is of such amplitude as partially to saturate the transductor core. Decreased generator voltage causes increased error signal, greater core saturation and increased exciter field current. Conversely, increased generator voltage reduces the error signal, ultimately to zero, when the exciter field current is reduced to minimum. Rectifier *A* prevents excessive generator voltage from causing reversal of the transductor control current.

Reference voltages may be obtained from primary cells, gas-discharge tubes, zener diodes and other devices. Discharge tubes, such as the Mullard 85 A2, which strikes at 115 volts and burns at about 85 volts ± less than 0·5 per cent, have been used in aircraft. A zener diode is a silicon diode, or small rectifier, which has a practically constant reverse breakdown voltage and which may be safely operated continuously at that voltage. These may be obtained for voltages from a few volts up to about 100 volts and are therefore particularly useful for low-voltage systems. Other devices used are non-linear resistors, such as barretters, and non-linear resonant circuits (see Ref. 11).

Magnetic Amplifiers. A magnetic amplifier may be defined as a transductor with additional components which increase the amplification of the device. Many types are known (Ref. 11) and one of the simplest types is represented in Fig. 6.14. It uses a feedback winding which provides an m.m.f. approximately

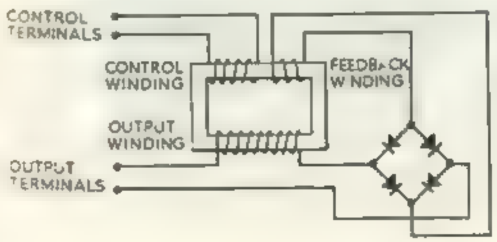


FIG. 6.14. *Simple magnetic amplifier.*

proportional to the a.c. load current and in the same sense as the control m.m.f. In practice a magnetic amplifier would probably be substituted for the amplifier and transductor shown in Fig. 6.13.

Provided a source of a.c. power is available it is possible to control the field current of a d.c. exciter, thereby replacing the regulator resistance, shown in Fig. 6.6 (*b*), with a magnetic amplifier, as shown in Fig. 6.15. Unless the system is capable of reliable initial excitation an a.c. supply is not normally

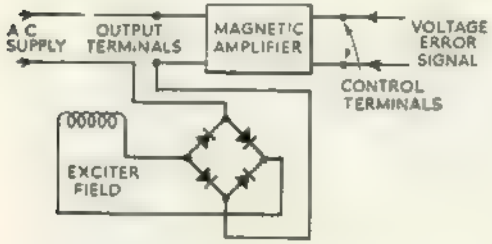


FIG. 6.15. *Magnetic - amplifier voltage regulator for the scheme shown in Fig.* 6.6 (b).

available. For this reason, and also because the complete regulator is heavier than the equivalent carbon-pile regulator, magnetic-amplifier-controlled d.c. exciters have not been greatly used. Further, the waveform of alternating current taken by magnetic amplifiers is sometimes severely distorted and their presence as a load on a power supply system is often undesirable.

Electronic Amplifiers. It would be possible to use an electronic amplifier in the system shown in Fig. 6.13 in place of the magnetic amplifier previously suggested, or in place of the amplifier shown in the diagram. This has been done in regulators for small a.c. generators, most of which have been part of converting equipment. Close regulation and fast response to changes of load and speed are the salient characteristics of electronic regulators. The fragility of some electronic valves, the requirement for filament and h.t. supplies, and the relative inefficiency of electronic power amplifiers have, however, limited their applications.

Transistor Amplifiers. With the development of silicon power transistors it is probable that transistor amplifiers will supersede electronic amplifiers for regulators and it is likely that, together with zener diode voltage references, they will challenge the position of the carbon-pile regulator. They have the advantages of ruggedness, of requiring only a low-voltage d.c. supply, of small size and weight, and, in some applications, of good efficiency.

A transistorized d.c. voltage regulator, utilizing the 28-volt supply was discussed under the heading *Transistorized Carbon-pile Voltage Regulator*. In this regulator, all but the final control of generator excitation current is effected by a transistor circuit.

COOLING

Much of the earlier discussion on the cooling of d.c. generators (see under *Cooling* in Chapter 5), is also applicable to a.c. generators. Several types of a.c. generators have been designed for cooling with air taken from one of the early stages of a gas-turbine compressor. This is a practice which ensures a flow of air whenever the engine is running, minimizes the length of air intake ducting and eliminates the air scoop. The generator built for the Comet 4, shown in Fig. 6.16, is cooled in this way from the third stage of the compressor. The temperature of air flow from compressors is always above ambient temperature, and temperatures as high as 140 deg. C. have been used. The normal temperature for the Comet generator cooling air is 135 deg. C. and the maximum working temperature of the generator is 200 deg. C. Another disadvantage of compressor bleed air is its oil vapour and mist content. This is particularly troublesome to a.c. generators having d.c. exciters, since oil on the exciter commutator causes increased resistance in the exciter field circuit and tends to prevent initial excitation. It has been estimated that a cooling air inlet temperature of about 120 deg. C. is the highest for which air cooling is economical.

More consideration has been given to liquid cooling in the case of a.c. generators partly because the absence of a commutator permits operation

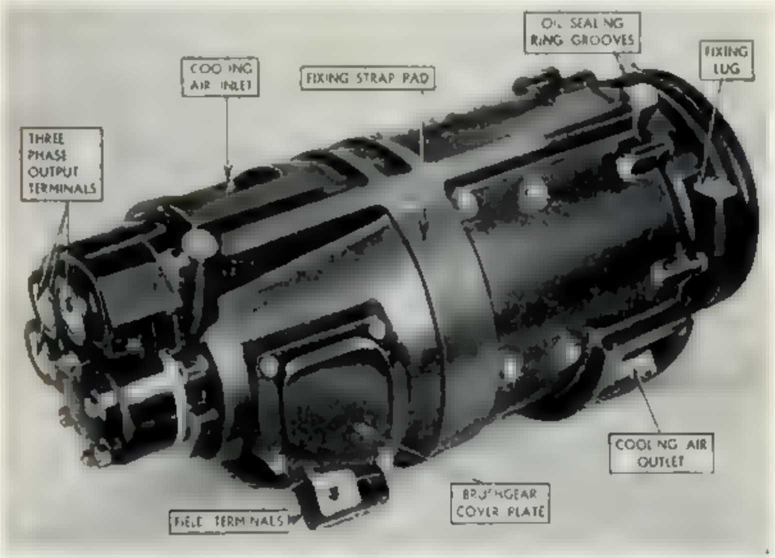


FIG. 6.16. *Three-phase generator, 26-volt, 17·5 kVA. Cooling air at 135 deg. C. is derived from the third stage of the main engine compressor. Speed range 4,000 to 10,000 r.p.m. Weight, 79 lb.*

under rather dirtier conditions, and partly because most new aircraft in the U.S.A. are fitted with a.c. generators. Oil-cooled machines have been developed in the U.S.A. having oil passages in both rotor and stator, as shown in Fig. 6.17. This arrangement requires oil seals on the shaft which may be expected to allow leakage of some oil into the interior of the machine. This cooling method transfers the heat of the machine to the oil, leaving the problem of cooling the oil to be dealt with elsewhere, either by the engine oil cooler, suitably enlarged to dissipate the extra heat, or by a separate oil cooler. Although the problem of heat dissipation has merely been transferred from the generator to the oil cooler, the latter can be specifically designed for cooling, whereas the internal configuration of an air-cooled machine is mostly determined by electrical considerations.

Oil is a much more effective coolant than air and this enables the oil-cooling ducts to be made much smaller in cross-sectional area than the air

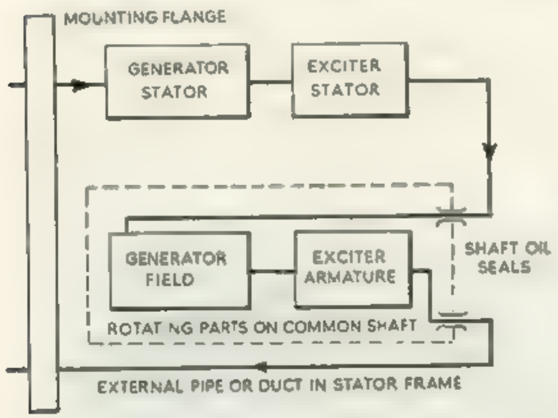
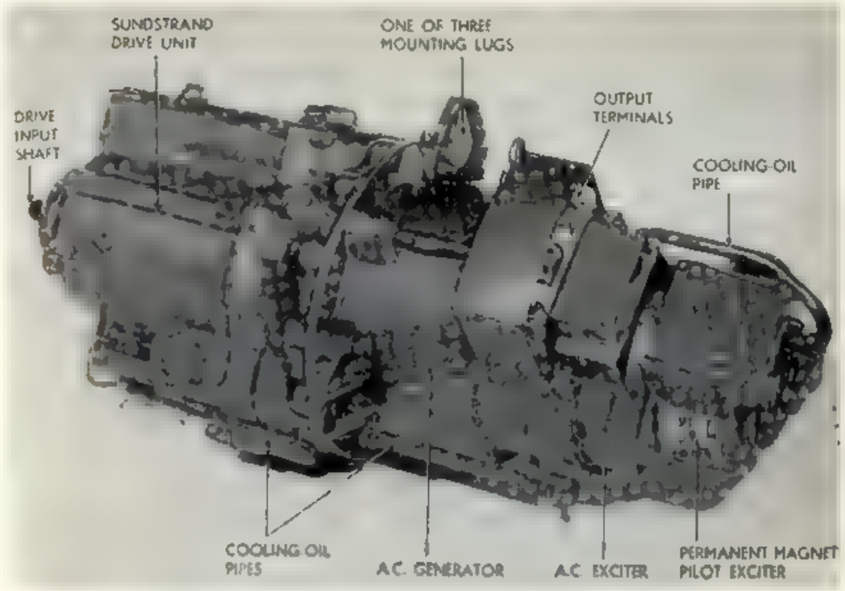


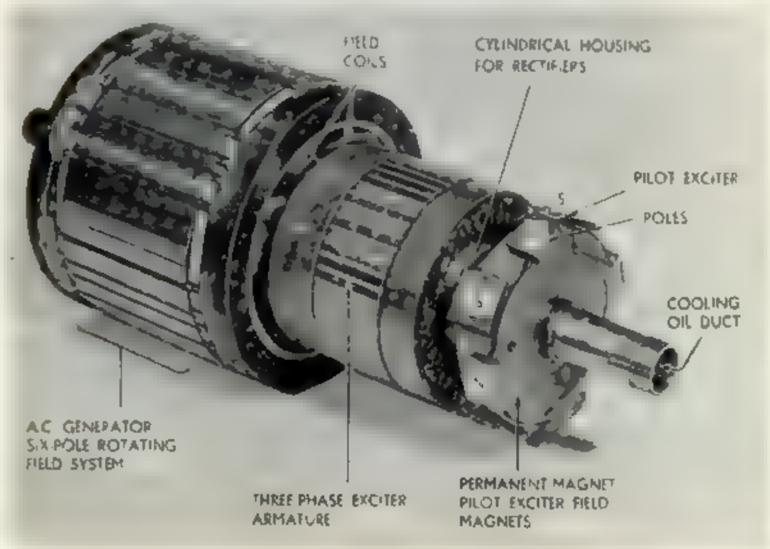
FIG. 6.17. *Indicating the routing of the oil-cooling circuit through a rotating field a.c. generator.*

ducts. As a result of this, oil-cooled generators are a little smaller than air-cooled generators. They are also unaffected by altitude and therefore likely to be suitable for a number of different types of aircraft. The effects of altitude are, of course, experienced by the oil cooler, unless, as discussed later, the aircraft fuel is used as a heat sink. An oil-cooled generator is shown in Fig. 6.18 (see also Fig. 6.19).

Water-vapour Cooling. A radically different method of cooling has been developed by Jack & Heintz Inc. in the U.S.A. In this method, water is sprayed, under pressure, from the rotor on to the internal surfaces of the generator. The water is boiled and released from the generator casing as superheated steam. For such a method to be successful the generator must almost certainly be of a brush-less type or have a sealed brush compartment, and bearings must be effectively sealed against the entry of moisture. A



(Above) FIG. 6.18. *Brush-less oil-cooled 40 kVA a.c. generator having a permanent-magnet pilot exciter, an a.c. main exciter and rectifiers assembled in the shaft. The generator is assembled to a Sundstrand constant-speed drive.* (Below) FIG. 6.19. *Rotor of the generator shown in Fig.* 6.18.



30 kVA generator which requires $8\frac{1}{2}$ lb. of water per hour when operating at full load in an ambient temperature of 260 deg. C. is shown in Fig. 6.20. The generator has no integral exciter and weighs 66 lb. The advantage of this method of cooling is that the machine is capable of operating at full load at any altitude. It can also operate safely in high ambient temperatures, the ultimate limit probably being determined by the mechanical strength of the machine structure. The flow of water to the generator is determined by stator temperature and is increased automatically in higher ambient temperatures.

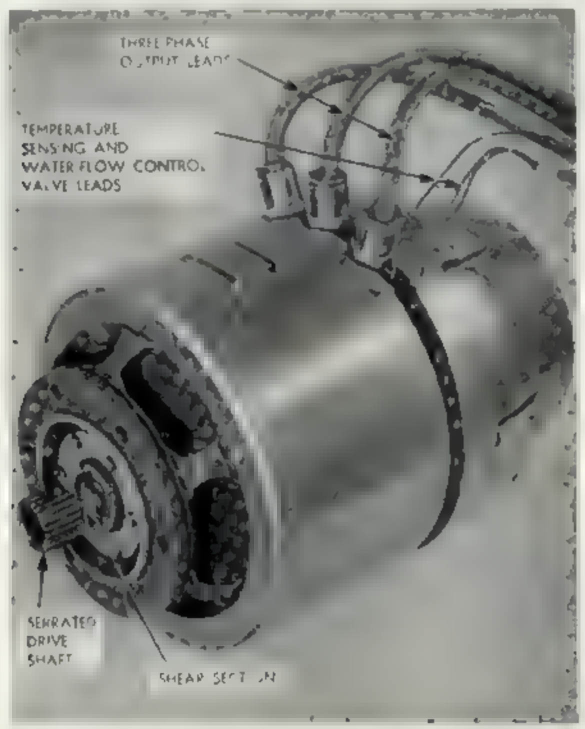


FIG. 6.20. *Water-vapour-cooled a.c. generator rated at 30 kVA*

Fuel as a Heat Sink. In an aircraft moving at very high speed the aircraft skin becomes heated and electrical equipment is liable to receive radiant heat from the skin and conducted heat through structural members. In addition, as explained in the section on *Blast Cooling* (Chapter 5), ram air collected by such an aircraft is subject to an adiabetic temperature rise so that cooling by forced convection may be impracticable. Under these conditions the use of the aircraft fuel as a heat sink may be worth while. Fuel has a specific heat of about 0·5 and a substantial temperature rise seems to be acceptable. Heat

added to fuel may be partly converted to engine thrust, but this advantage is small compensation for the fire risk arising from pipe lines carrying heated fuel. The use of an oil system to transfer heat from electrical equipment to the fuel seems more readily acceptable than direct systems in which the fuel is passed through the equipment.

The high-speed flight conditions which would justify the use of fuel for cooling the generators will also give rise to extra cooling requirements for engine oil, hydraulic oil and the crew. It appears unlikely that the fuel heat sink will be adequate for all purposes and that it will be necessary to restrict the use of the heat sink to those flight conditions where it is essential.

CONSTRUCTIONAL DETAILS

The frequency, f, in c/s, of a salient-pole, rotating-field a.c. generator is directly related to the operating speed, n, in r.p.second by the relationship:

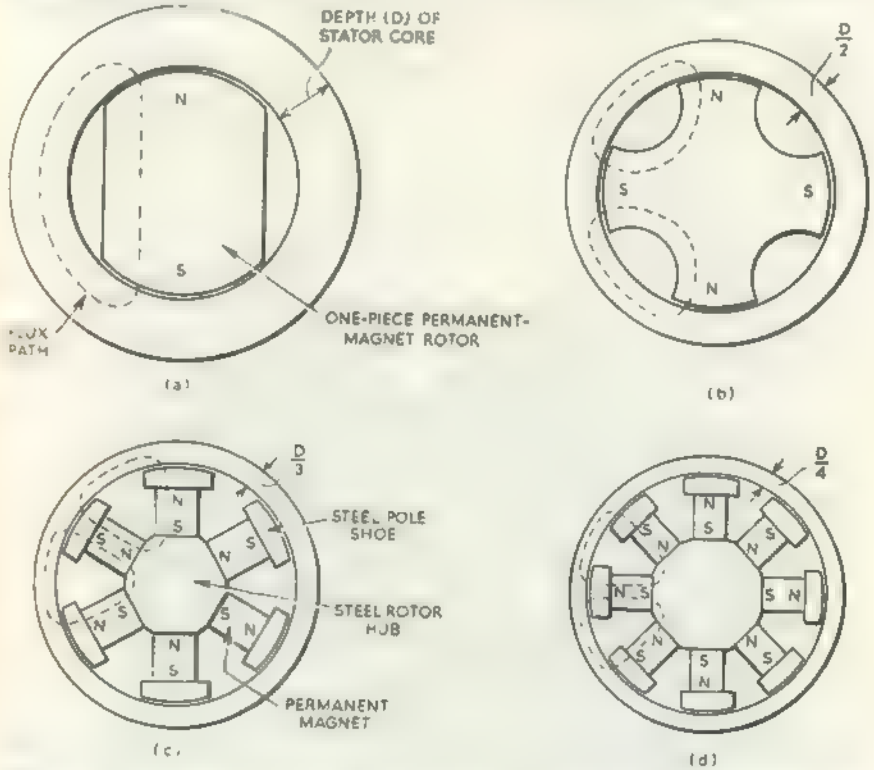


FIG. 6.21. *How stator-core depth varies inversely as the number of poles, speed and output power being constant:* (a) *and* (b) *represent permanent-magnet a.c. generators in which the rotor is a single-piece magnet;* (c) *and* (d) *represent generators with built-up rotors.*

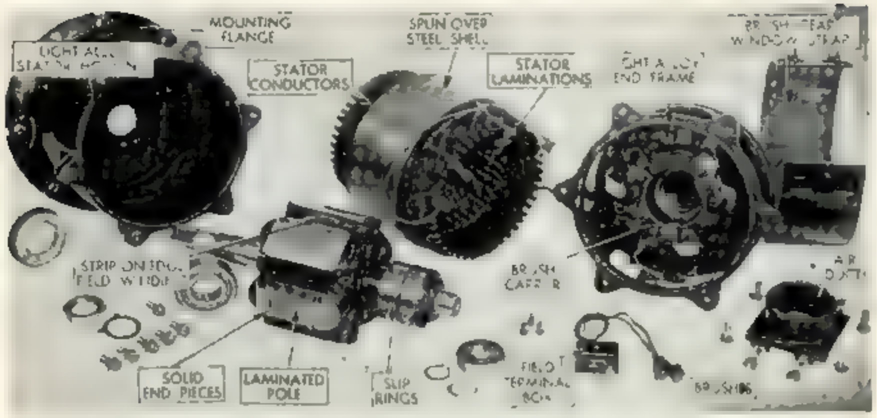


FIG. 6.22 *Components of an 8 kVA wide-speed-range a.c. generator.*

$f=np$ (equation 15), where p is the number of pairs of poles. When the frequency is not precisely specified, as may be the case for variable-speed generators for rectified a.c. systems, f, n and p may be chosen for minimum weight. Too few pairs of poles, p, leads to a heavy design since the depth of the stator core is increased as p is reduced. This is illustrated in Fig. 6.21. Stators with too many poles are difficult to construct and cause high flux leakage between the pole tips. Speed, n, is limited by bearing performance and constructional difficulties. A high n is desirable, however, because the total air-gap flux is inversely proportional to n, and iron weight is approximately proportional to air-gap flux. High frequencies incur high eddy-current losses in stator conductors and in the iron, and high hysteresis losses. From these considerations it is generally agreed that a frequency of about 400 c/s and either four pairs of poles operating at 6,000 r.p.m., or three pairs of poles operating at 8,000 r.p.m., gives the lightest designs.

Fig. 6.22 shows the components of the 8 kVA generator previously referred to which has a six-pole rotor. The armature windings of this machine are conventional but, owing to the relatively high frequency of the output current, the radial depth of the conductors has been restricted to avoid excessive eddy-current losses in the copper. Stator laminations are contained in a mild-steel shell and retained by spinning the shell over at the ends. The stator assembly is a force fit in the light-alloy housing or frame, one end of which carries the drive-end bearing and is flanged to bolt to the aircraft engine or auxiliary gear box. The other end of the housing carries a detachable frame in which the brushgear is mounted.

Slip rings are of such metals as phosphor bronze and cupro-nickel and are limited in diameter by the brush rubbing speed, which should not exceed

about 10,000 ft. per min. Two or three brushes, displaced circumferentially, are positioned to bear on each ring, the displacement being such that the brush axes lie in different planes. Two brushes, for example, would probably be positioned 90 deg. apart, but not diametrically opposite. This ensures that any particular mode of vibration is unlikely to affect all brushes equally. An assembled wide-speed-range generator having an output of 22·5 kVA up to 30,000 feet is shown in Fig. 6.23. Its operating speed is 8,000 r.p.m. for a 400 c/s output and its over-speed rating is 10,000 r.p.m. The machine weighs 42 lb. giving a specific weight of less than 2 lb. per kVA. The cooling-air inlet is at the slip-ring end of the machine and the outlets are near the mounting flange. A flow of 120 cu. ft. a minute is required and at this rate the pressure drop across the generator is 7 in. of water. As mentioned in Chapter 5 (see *Forced Convective Air Cooling*), above 30,000 feet and up to 50,000 feet the rating is reduced to 15 kVA. Slip rings are carried on an extension of the shaft overhanging the bearing, and are contained in a ventilated compartment of reduced diameter at the end of the machine. The terminals of this machine are of the S.B.A.C. type, a description of which is given in Chapter 10.

A constant-speed generator made by the English Electric Company is shown in Fig. 6.24. This is rated at 40 kVA and is designed to operate at 6,000 r.p.m. Its weight is 99 lb., length 20 in. and height 13½ in. This machine has a built-in d.c. exciter, and account must be taken of this when comparing

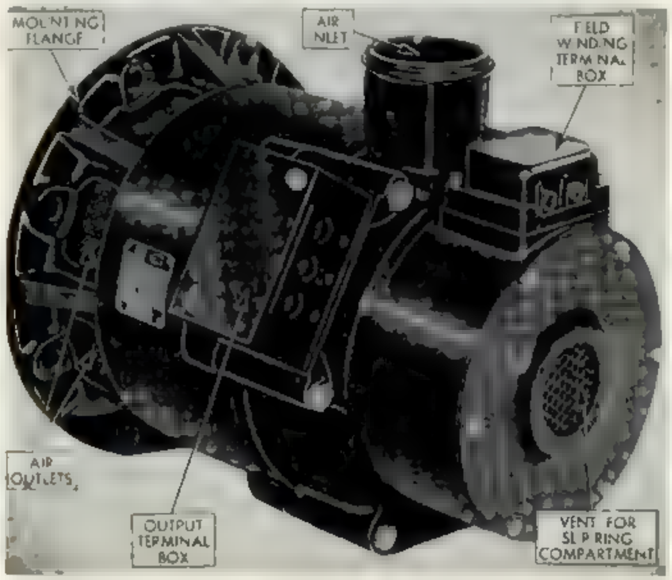


FIG. 6.23. *Wide-speed-range a.c. generator, 22·5 kVA, weighing 42 lb.*

specific weights. The 5-minute overload and over-speed ratings are 60 kVA and 11,000 r.p.m.

The development of high-speed drives, air turbines and gas turbines which operate most efficiently at high speeds, has created a requirement for high-speed generators in order to eliminate or minimize intermediate gearing. This has led to the development of two-pole generators operating at 24,000 r.p.m., the highest speed at which current at 400 c/s can be generated. The problem of centrifugal forces on the rotor windings has been met by using a non-salient or turbo type of rotor, in many ways models of those used in 50 c/s, 3,000 r.p.m. power-station generators. Fig. 6.25 shows an air-turbine-

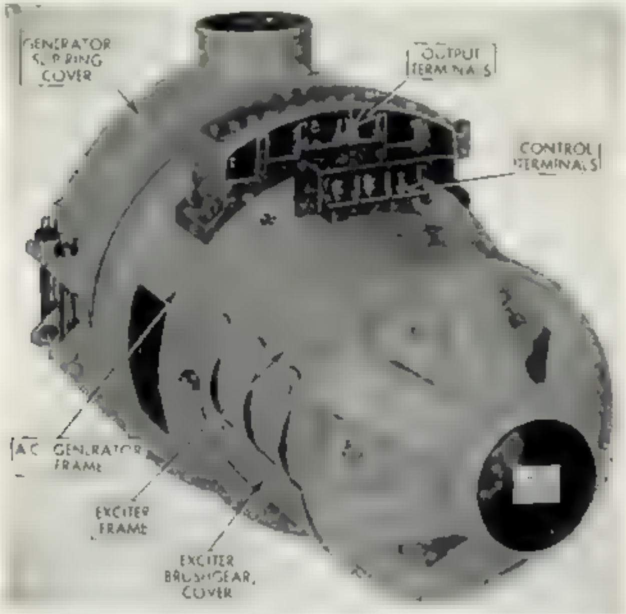


FIG. 6.24 *Constant-speed a.c. generator, 40 kVA, with built-in d.c. exciter.*

driven generator of this type. A Westinghouse (U.S.A.) development, known as the Turbonator, because it is a combined air turbine and a.c. generator or alternator, also uses a two-pole design.

In this case the rotor is a solid steel forging, probably giving the required strength with minimum weight and incidentally functioning as a damper winding. Slot ripple and iron losses are minimized by using rotor slots which are almost closed; these are convenient for retaining the windings although in manufacture the windings may be difficult to fit. The winding "overhangs" require special attention and in this machine are wrapped with silicone-

impregnated glass tape which is bonded with a high-temperature plastic material. After bonding, these wrappings are machined to receive shrunk-on titanium rings. Titanium is used because it has better strength at high temperatures than non-magnetic steels, and therefore gives lighter rings.

MOUNTINGS AND DRIVES

Much of the earlier discussion (see *Mountings and Drives*, Chapter 5) is also applicable to a.c. generators. Owing to their later introduction and generally larger size, a.c. generators have not been so restricted by mounting-

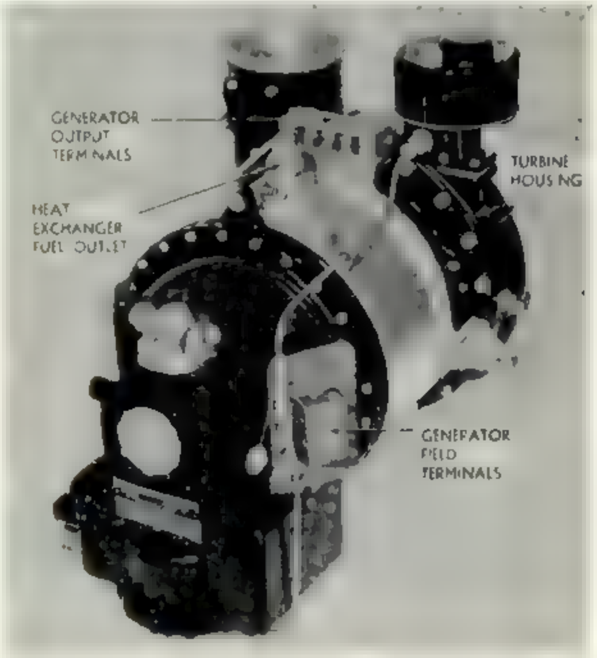


FIG. 6.25. *Air-turbine a.c. generator unit for operation from main engine compressor bleed.*

flange diameters as some of the medium-sized d.c. generators. To minimize overhang moments, the exciters, pilot exciters and slip rings are invariably fitted at the non-drive end.

A type of mounting not previously mentioned may be seen on the generator shown in Fig. 6.10. This machine, rated at 50 kVA and weighing 92 lb., has two mounting lugs, one of which can be seen at the top of the photograph. They are near the centre of gravity of the machine or, more precisely, the plane perpendicular to the machine axis which passes through

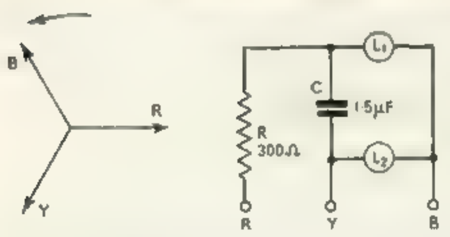


FIG. 6.26. *Voltage diagram of a three-phase supply of sequence* R, Y, B, *and a circuit for checking the sequence of a 200-volt, three-phase, 400 c/s supply.* L_1 *and* L_2 *are 15-volt, 250-watt lamps. When the circuit is correctly connected* L_1 *is brighter than* L_2.

the centre of gravity, and are spaced 100 deg. apart circumferentially. Precise location of the drive, and some additional support, is given by the mounting flange at the extremity of the specially extended drive end bearing clamp. This flange is secured to the engine or gearbox casing with a manacle ring.

The 17·5 kVA generator, shown in Fig. 6.16 has both bearings lubricated with oil from the engine gearbox. The oil flows into the hollow shaft, through holes in the shaft wall to both bearings, and returns to the gearbox through holes machined in the main frame casting. Oil is prevented from seeping into the generator by the use of air pressurized seals, the air being obtained from the fourth stage of the turbine compressor. Quill shafts incorporating shear sections and friction dampers have been used, as for d.c. generators, but solid shafts are preferred by most British designers.

SERVICING

Some of the earlier discussion on the servicing of d.c. generators is also applicable to a.c. generators. The latter are generally easier to service owing to the simpler brushgear and absence of a commutator. The brushes are less troublesome because they run on slip-rings and carry only the excitation current. Brushgear in a.c. generators is often more accessible than in d.c. generators, partly because it is less dense and partly because of more favourable mechanical layouts. The overhanging of slip-rings beyond the generator bearing, as shown in Fig. 6.10, favours accessibility. Brushgear and slip-ring inspections are likely to be carried out after 200 to 300 hours of operation, and overhauls after 300 to 800 hours.

Testing after overhauls follows the same lines as for d.c. generators, but there is an important additional check on the phase sequence of the output at the generator terminals. Phase sequence is the order in which each of the terminal voltages rises to its maximum value, and is always specified. Although many loads, such as lighting and heating loads, are quite insensitive to phase sequence, it is vital for generators operating in parallel and for loads which include induction and hysteresis motors. A circuit, shown in Fig. 6.26, is commonly used for this check and serves as an example of a circuit which operates differently when the phase sequence of its supply is changed.

SPECIAL A.C. GENERATORS

ROTATING-RECTIFIER GENERATOR

THIS machine is completely brush-less and is arranged as shown in Fig. 6.27. Excitation current in the field winding of the exciter is d.c., and voltage regulation may be achieved by controlling this current as for a d.c. generator. Alternating currents induced in the exciter output windings are rectified by rectifiers which are mounted around or inside the shaft and the steady current is passed to the generator field windings. A three-phase exciter output winding and a full-wave rectifier circuit are used in order to minimize ripple on the generator field current since this would cause a similar ripple on the generator output. Field current for the exciter may be obtained by rectification of part of the generator output or from a pilot exciter, as previously discussed.

The problems which delayed the development of this type of generator were the size of rectifiers, their performance under centrifugal stress and their temperature limitations. Selenium rectifiers were too large and their upper temperature limit was substantially less than the economical operating temperature of the rotor. Germanium rectifiers, although smaller, had a similar temperature limitation. Silicon rectifiers, after initial development and study of mounting and cooling methods, have proved to be satisfactory.

The mounting of rotating rectifiers has taken two forms, radial and axial. A radial assembly, as shown in Fig. 6.8, requires the minimum departure from the normal form of construction but subjects the rectifier elements to large centrifugal forces. At 6,000 r.p.m. a mass of one-tenth of a pound mounted at a radius of one inch, experiences a force of 100 lb. Despite this, radial assemblies appear to be practicable for silicon rectifiers. Axial assemblies do not subject the rectifiers to such large centrifugal forces but do require a large-diameter hollow shaft of special design. The hollow shaft forms a natural cooling duct and this arrangement may be preferable for oil-cooled machines. Fig. 6.19 shows a rotor containing axially mounted rectifiers.

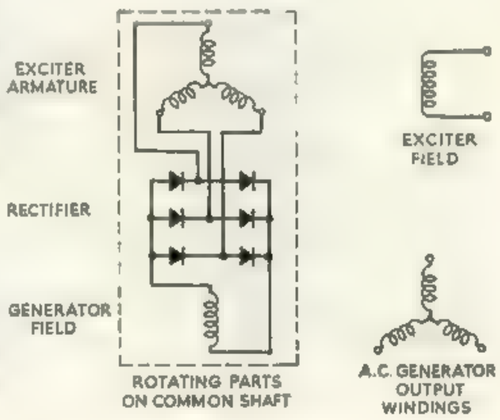


FIG. 6.27. *Schematic diagram of a rotating-rectifier type of a.c. generator. There are no electrical connexions between the rotor and stator.*

PERMANENT-MAGNET GENERATORS

A generator having a permanent-magnet field can be completely self-contained and independent of external supplies or equipment. It is also brush-less. The disadvantages of such machines are firstly the difficulty of voltage regulation and secondly the necessity to compromise between weight and stability. No simple and efficient method is known for regulating the voltage to a constant value over a range of load current and load power-factor. By design, the terminal voltage/load-current curve can be made fairly flat for a limited power-factor range, but large changes of power-factor cause large changes of voltage. The method which most nearly approaches the requirement is that of fitting toroidal windings round the stator core as indicated in Fig. 6.28. Direct current in these windings controls the state of magnetic saturation of the core and regulates the output voltage over a limited range. Unlike normal excitation current, this control current must have its highest value at no-load. The extra weight added and power dissipated in the generator, the high m.m.f. required to saturate the core and the limited range of voltage regulation obtainable, are reasons why this method has not been applied to aircraft permanent-magnet generators.

The stability of a permanent-magnet generator is the ability of a machine to generate its rated open-circuit voltage after being short-circuited or subjected to current surges which tend to demagnetize the magnet. The lightest machine is generally the most readily demagnetized and, since short-circuit faults occur from time to time, such machines are not usually acceptable for aircraft applications.

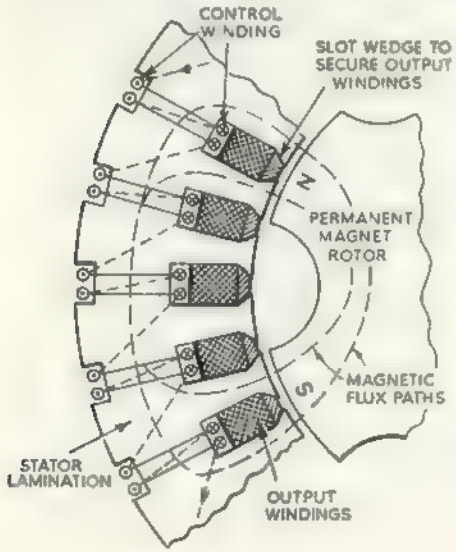


FIG. 6.28. *Cross-sectional diagram of a permanent-magnet a.c. generator fitted with a winding for regulating output voltage by controlling the magnetic saturation of the stator core.*

Although permanent-magnet generators are not at present practicable as main generators, they are used as pilot exciters, where the problem of voltage regulation is overcome by series control of the exciter output. This method would require a prohibitively large and wasteful regulator if applied to a main generator but it is acceptable on a small scale. Similarly, owing

to the small ratings of pilot exciters, it is practicable to accept relatively heavy machines to obtain good stability. In order to understand stability it is necessary to consider the processes of magnetization and demagnetization to which the excitation magnet of a permanent-magnet a.c. generator is subjected, both during manufacture and operation. Fig. 6.29 (*a*) shows the relationships between flux density in the magnet, *B*, and *H*, the magnetizing force applied to the magnet. Curve *OA* represents initial magnetization from the unmagnetized to the saturated state. On removal of the magnetizing force, the magnetic flux density, *B*, is reduced to a value given by ordinate *CD*, if the magnet is fitted with a keeper, or some value such as *EF* if the magnet is itself required to provide a magnetizing force.

The essential property of a keeper is that it provides a low-reluctance

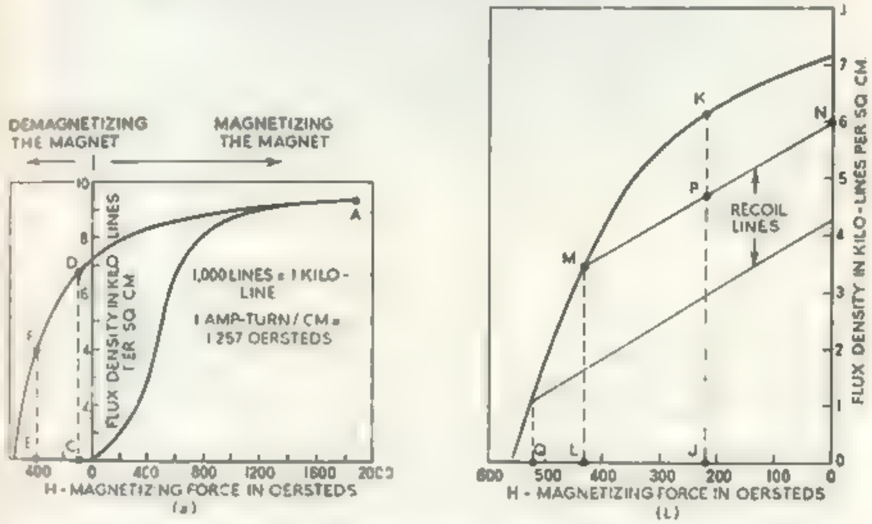


FIG. 6.29. (a) *Magnetizing and demagnetizing curves of Alnico permanent-magnet material.* (b) *Curves showing the operating conditions of an Alnico field magnet in a permanent-magnet a.c. generator.*

flux path between the two magnetic poles so that magnetic flux may be set up with a minimum magnetizing force. The small magnetizing force required by the keeper is represented by *OC*, and the larger force required to pass flux through the space between the poles when the keeper is not in position is represented by *OE*.

The magnetizing force required from the magnet to establish the working flux in a generator is greater than *OC* but less than *OE* and is represented by *OJ* in Fig. 6.29 (*b*). This is because the reluctance of the flux path presented to the magnet, which is part of the stator core and two air gaps in series, as

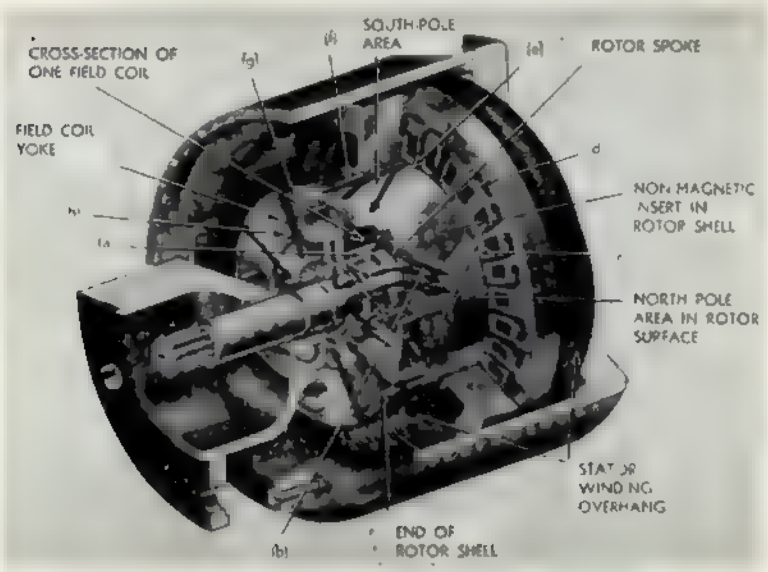


FIG. 6.30. *Secsyn a.c. generator, sectioned to show main flux paths.*

shown in Fig. 6.28, is greater than that of a good keeper but much less than that of the space between the poles. The working flux density is represented by *JK* which is a direct indication of the no-load terminal voltage. In operation, armature reaction, which arises particularly from lagging-power-factor load current, sets up a demagnetizing force which is experienced by the excitation magnet. This is represented by *JL* and it can be seen from Fig. 6.29 (*b*) that when this additional force is sustained by the magnet the working flux density is reduced from *JK* to *LM*. On removal of the load, the demagnetizing force, *JL*, is emoved, but the working flux density is not restored to its former value, *JK*. Instead, the magnet recovers along the subsidiary curve *MN* so that after removal of the load the working flux density is represented by *JP* which is less than *JK*. The no-load voltage is also reduced in the ratio *JP*/*JK*. Repeated application of the same load would produce no further changes but a single application of a greater load, setting up a demagnetizing force represented by *JQ* would cause a further reduction of working flux and no-load voltage.

The maximum possible output is obtained when the magnet is fully magnetized and not subsequently subjected to a demagnetizing force greater than that occurring in the generator at full load. This means that it must not be removed from the magnetizer or the machine stator without a keeper, nor must the generator be overloaded. In this condition a generator is termed

unstabilized and, as explained above, is not usually a practical machine. The application of a momentary short-circuit would stabilize the machine so that subsequent short-circuits would have no effect but the output voltage of the machine would be greatly reduced. Removal of the magnet without a keeper would have a similar effect, greater or less than that of a short-circuit, depending on the design of the generator. It is therefore necessary to design permanent-magnet generators so that the required output is obtained after stabilization by either short-circuit or armature removal and forego the weight saving which could be realized if unstabilized operation were acceptable. Ref. 6 discusses design methods of minimizing this penalty.

THE SECSYN GENERATOR

This is a generator of unusual construction which has recently been developed by Jack & Heintz Inc. in the U.S.A. Fig. 6.30 shows a cut-away view of the machine. The rotor is unique although the stator is conventional The rotor consists of a thin-walled tube of magnetic material which carries hexagonally shaped inserts of non-magnetic but electrically conducting material. These inserts surround areas which form north poles in the rotor surface. The tube is supported by heavy spokes of magnetic material positioned between the north poles and the shaft. Field m.m.f's are established by stationary field coils, concentric with the machine axis and located within the "overhang" of the tube, one at each end of the machine.

Each coil is carried in a soft-iron yoke and sets up flux which takes the following path (see Fig. 6.30). (*a*) Inwards through the coil centre, partly in the shaft and partly in the coil yoke, crossing the air gap between the two. (*b*) Radially outwards along the spokes of the rotor structure. (*c*) Across the air gap and into the stator. (*d*) Circumferentially around the stator to an adjacent pole area. (*e*) Radially inwards across the air gap and into the rotor surface. Here there is no spoke under the rotor tube and flux is constrained to follow an anxial path (*f*) outwards along the rotor tube. (*g*) Radially inwards across an air gap between the rotor tube and field-coil yoke. (*h*) Radially inwards through the coil yoke.

The virtues of the machine are the ruggedness of the rotor and the absence of brushgear, and also that the output voltage may be regulated in the conventional manner by controlling the field current. The disadvantage that the flux paths include four air-gap crossings, instead of the usual two, is minimized by making the gaps as short as possible and of the largest possible area. It is claimed that less than 10 per cent of the total field m.m.f. is developed across the gaps. The future of this generator in aircraft has still to be established. The type of field coils used in this machine are usually termed *homopolar*; they are also used in the homopolar inductor generator discussed in the next section.

INDUCTOR GENERATORS

In 1901 Georges Guy of Paris claimed patent rights for a machine "which allows any frequency or voltage to be obtained even with the lowest speed of revolution", and which he forcast was "destined to supersede other machines for almost all uses". Although unduly optimistic, variations of his machine have since been used for special applications where its inherent ability to generate high frequencies at relatively low speeds has been required. Notable among these applications is the development of radio-frequency generators by F. W. Alexanderson about 1909, culminating in the construction of a 2 kW, 100,000 c/s generater. This application subsided with the development of large transmitting valves. The aircraft radar equipments developed during the second world war required power at about 1,500 c/s, a frequency which can easily be provided by an inductor generator, and since the generator has the further advantages of being without brushes or rotating windings, it was chosen at the outset for British aircraft. Although it is no longer used extensively as an engine-driven generator, it is commonly used in motor-generators, which are described in Chapter 8. It is also used as an exciter for main a.c. generators as previously described (see *Built-in Exciters*), and as a main generator in some guided missiles.

Principle of Operation. The principle of the inductor generator is illustrated in Fig. 6.31. Steady current passed through the field windings sets up a flux in the path shown. The magnitude of the flux depends on the rotor position and varies continually when the rotor is rotated. The flux value at any time, t, may be expressed in terms of the maximum and minimum values of flux, ϕ_{max} and ϕ_{min} respectively, as follows:

$$\phi = \tfrac{1}{2}(\phi_{max}+\phi_{min})+\tfrac{1}{2}(\phi_{max}-\phi_{min}) \cos 2\pi ft \qquad (16)$$

where f is the frequency of flux changes in c/s. The first term, $\tfrac{1}{2}(\phi_{max}+\phi_{min})$, represents the average value of flux, which is independent of rotation. The second term is a flux which changes with rotation, it has been assumed, in a manner following a cosine law. This assumption is partly justified by the fact that practical generators are designed with this as a desirable objective. The

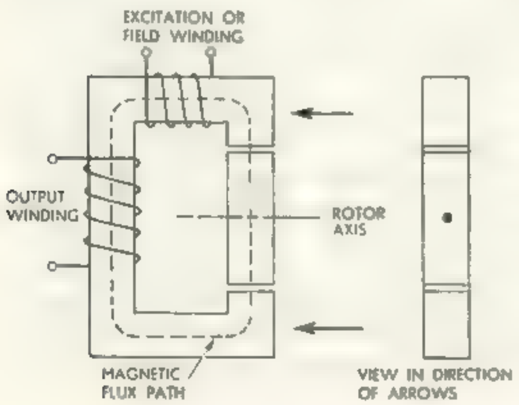


FIG. 6.31. *The principle of the inductor generator.*

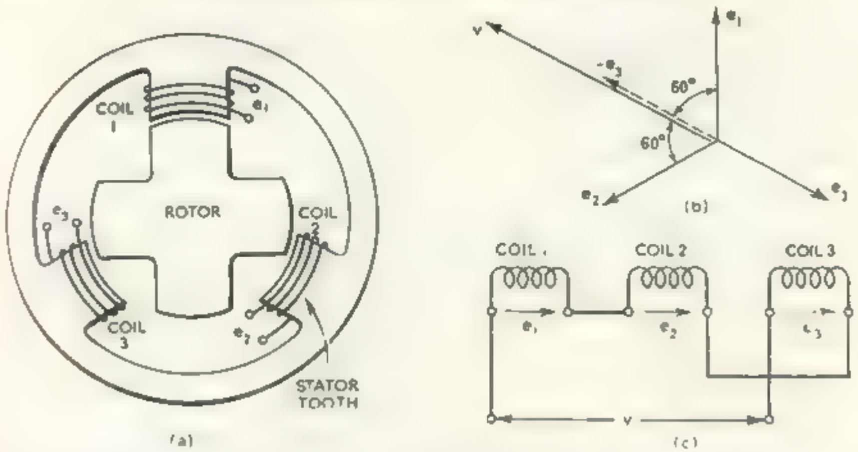


FIG. 6.32. (a) *One of the simplest arrangements of homopolar-type inductor generator.* (b) *Voltage diagram for the generator shown in* (a). *The value of output voltage, v, in terms of the coil e.m.fs.* $e_1, e_2, e_3 = e_1 \cos 60$ *deg.* $+ e_2 \cos 60$ *deg.* $+ e_3 = \tfrac{1}{2}e_1 + \tfrac{1}{2}e_2 + e_3 = 2e$*; if* $e_1 = e_2 = e_3 = e$. (c) *Method of connexion of the generator shown in* (a) *so that the terminal voltage is twice the coil voltage.*

changing flux is linked with the output winding and the induced voltage in the winding is given by:

$$e = -T d\phi/dt \qquad (17)$$

where T is the number of turns on the output winding, and $d\phi/dt$ signifies the rate of change of flux. Differentiating the expression for ϕ, given in equation (16), and multiplying by $-T$, gives:

$$e = T\pi f(\phi_{max}-\phi_{min}) \sin 2\pi ft \qquad (18)$$

Thus the induced voltage depends on the difference between the maximum and minimum flux levels. This is a fundamental feature of the generator which makes it heavier than other types in which the output voltage is proportional to the maximum flux level. A low value of minimum flux is therefore a primary design objective, but even in the best designs it is still a significant value.

The frequency of the generated voltage is equal to the number of flux maxima, or minima, per second. This is given by the number of rotor teeth, or projections, multiplied by the number of revolutions per second. In Fig. 6.31 two teeth are shown and two flux maxima occur per revolution. In practice it is easy to make a machine with a large number of rotor teeth and hence generate a high frequency at moderate speeds of rotation. Summarizing,

$$\text{Frequency} = (\text{Number of rotor teeth}) \times (\text{Speed in r.p.second}) \qquad (19)$$

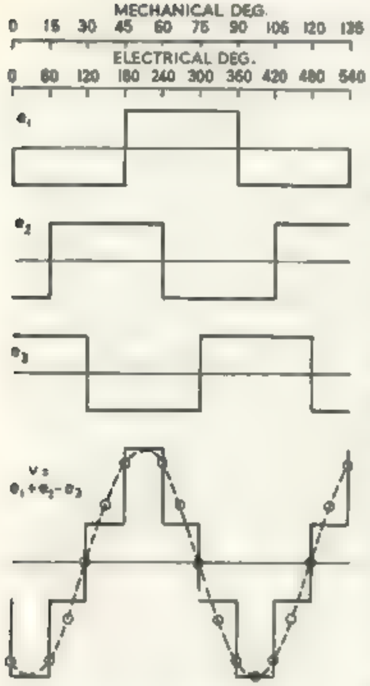


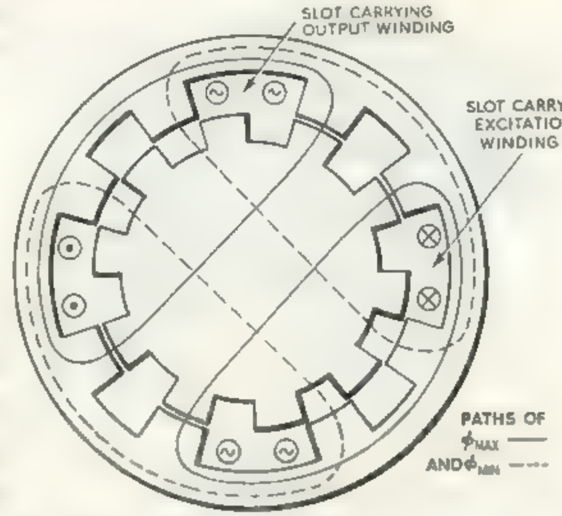
FIG. 6.33. *Showing that if the three coil e.m.f's of the generator shown in Fig.* 6.32 (a) *are rectangular in waveform, the terminal voltage is approximately sinusoidal.*

Homopolar Inductor Generator. The simple arrangement shown in Fig. 6.31 is not practical, firstly because an alternating e.m.f. would be induced in the excitation winding. This would probably cause a.c. to flow in the excitation circuit with consequent heating and power loss. Secondly, some development is necessary in order to improve the induced voltage wave-form. A simple practical arrangement is shown in Fig. 6.32 (*a*). This is termed a homopolar inductor generator and has a single excitation coil wound inside the stator. This sets up an axial m.m.f. which gives rise to flux which emanates radially from the rotor teeth. The arrangement may be better visualized by reference to Fig. 6.38. Fig. 6.32 (*a*) is a simplified sectional view of the machine shown in Fig. 6.38, on the plane *AA*. It will be noticed that the number of rotor and stator teeth differ by one. If they had been equal the flux pulsations occurring with rotation would have linked with both output and excitation windings, but because different numbers of teeth have been chosen, the flux through the excitation winding is almost independent of rotation. The frequency of the e.m.f. induced in coil 1 of the output winding, which is wound round stator tooth 1, is determined by the fact that four times during each revolution a rotor tooth coincides with this stator tooth.

The flux therefore passes through four cycles per revolution and the e.m.f. frequency is equal to the number of rotor teeth multiplied by the speed in r.p.second. The e.m.f's in the other stator coils, e_2 and e_3, are of the same frequency but are shifted in phase as indicated in the voltage diagram Fig. 6.32 (*b*). If the coils are connected as shown in (*c*) a terminal voltage, $v=2e$ is obtained if $e=e_1=e_2=e_3$.

The voltage diagram is correct only if all the e.m.f's are sinusoidal or free from harmonics. Even if this is not so, suppression of some harmonics with a consequent improvement of the terminal waveform is obtained by connecting the coils as shown in (*c*). This is illustrated in Fig. 6.33 where the

FIG. 6.34. *Cross-sectional diagram of a simple heteropolar inductor generator.*



coil e.m.f. waveform is shown as rectangular, as would be the case if the flux passing through the stator teeth were either increasing or decreasing at a constant rate.

Heteropolar Machines. In heteropolar generators both the excitation and the output windings are carried in stator slots as indicated in Fig. 6.34. The absence of the axial excitation coil causes the heteropolar machine to be much shorter although slightly larger in diameter than a homopolar machine of the same rating. The construction is preferable because it more closely resembles that of conventional electrical machines and because it is substantially lighter. The principles described for the homopolar generator apply also for the heteropolar; ϕ_{max} and ϕ_{min} follow the paths indicated in Fig. 6.34 and output frequency is determined, as before, by the rotor speed and the number of rotor teeth. The paths of ϕ_{max} and ϕ_{min} are interchanged when the rotor has moved one-half of a tooth pitch. Owing to the fact that the flux paths alternate, this machine is sometimes called a "swinging field" machine.

Open-circuit Characteristic. A typical open-circuit curve relating terminal voltage and field current is shown in Fig. 6.35. Unlike those of most types of generator it shows a reduction of voltage when the field current is increased to values causing

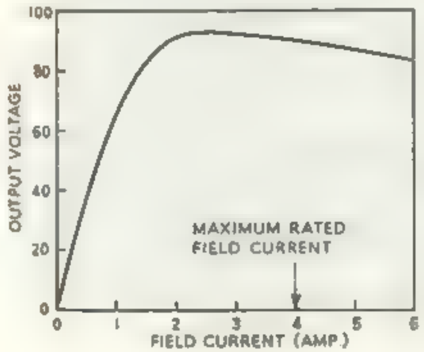


FIG. 6.35. *Open-circuit characteristic for a generator similar to the one shown in Fig.* 6.38.

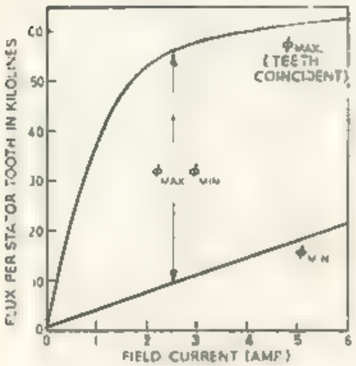


FIG. 6.36. *Curves showing how maximum tooth flux approaches saturation, whereas minimum flux does not.*

magnetic saturation. This occurs because output voltage is proportional to the difference between ϕ_{max} and ϕ_{min} and after saturation has been reached ϕ_{max} is almost unaffected by further changes of field current, whereas ϕ_{min} continues to increase. Curves showing how ϕ_{max} and ϕ_{min} increase with field current are shown in Fig. 6.36.

Load Characteristics. On load, voltage regulation is inherently high owing to the high reactance of the output winding and the effect of armature reaction. Lagging-power-factor loads give rise to serious demagnetizing armature reaction, and large changes of excitation current would be necessary to maintain constant output voltage if such loads were imposed. Because of this it has been the usual practice in aircraft to correct load power-factors to near unity by fitting series capacitors. Owing to the relatively high operating frequencies and small power ratings, this has generally been possible with small capacitors of negligible weight.

Construction. One of the larger inductor generators designed for aircraft is shown in Fig. 6.37. It is rated at 6 kVA and weighs 53·6 lb. It is of

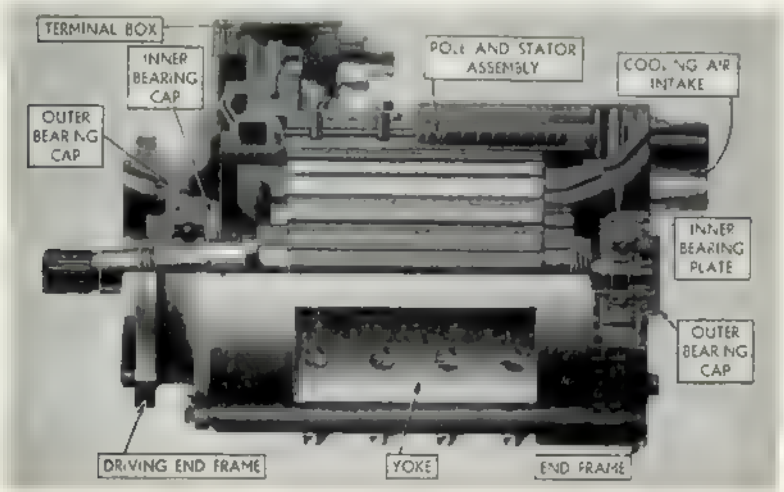
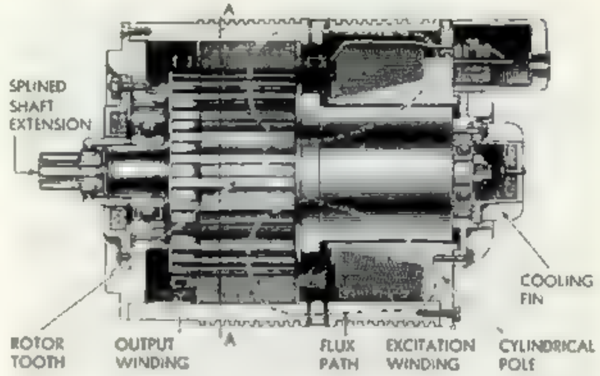


FIG. 6.37. *Heteropolar inductor generator rated at 6 kVA.*

FIG. 6.38. *Homopolar inductor generator, ½ kVA, a type used extensively in the early part of the second world war.*



heteropolar construction having both the output and excitation windings on the stator, and a rotor consisting only of laminated iron. The rotor has 24 teeth, thus the magnetic flux alternates 24 times per revolution. The normal speed for the machine is 4,800 r.p.m. (80 r.p.second) and the normal output frequency is therefore $24 \times 80 = 1920$ c/s. The over-speed rating is 6,000 r.p.m. for 5 minutes. The shapes of the rotor and stator slots and teeth influence the manner in which the magnetic flux varies with rotation, and therefore the shape of the output voltage waveform. This machine, in common with most inductor generators, has slots which are approximately rectangular. This shape is easily cut and is found in practice to give satisfactory results. Harmonics in the output waveform are more easily minimized by choosing appropriate connexions for the output winding coils and sometimes by skewing the slots, than by machining specially shaped slots.

Air cooling of this machine is facilitated by the axial slots in the rotor surface, since these allow a free flow of large volumes of air from end to end. This particular generator has a fan mounted on the shaft at the drive end and is also provided with an inlet for air-blast cooling. Incoming air is ducted to the drive end through axial vents near the centre of the rotor and returned in the opposite direction through the air gap and slots in the rotor surface.

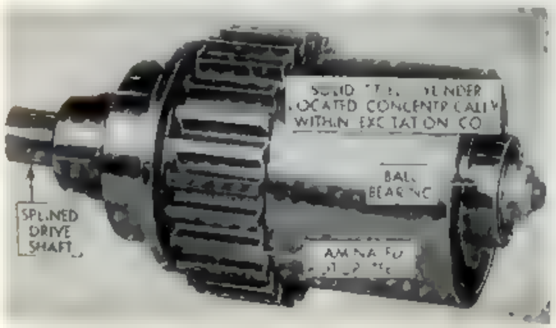


FIG. 6.39. *Rotor of a homopolar generator of the type shown in Fig.* 6.38.

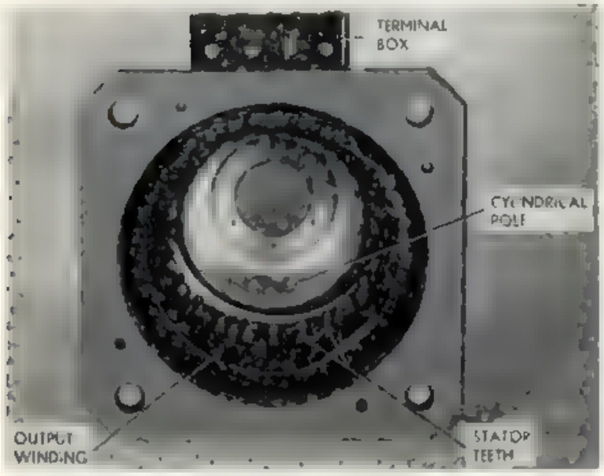


FIG. 6.40. *Internal view of a stator of a homopolar generator similar to the one shown in Fig. 6.38, taken from the drive end.*

A sectioned diagram of a $\frac{1}{2}$ kVA homopolar inductor generator is shown in Fig. 6.38 and a rotor and stator for a similar machine in Figs. 6.39 and 6.40. The view of the stator, Fig. 6.40, shows the output windings in the stator slots, but the excitation coil cannot be seen because it lies in the cavity between the cylindrical pole at the remote end of the machine and the machine frame. In Fig. 6.38 it can be seen that the frame is ribbed over the excitation and stator coils in order to assist cooling.

An interesting hybrid machine, developed during the second world war

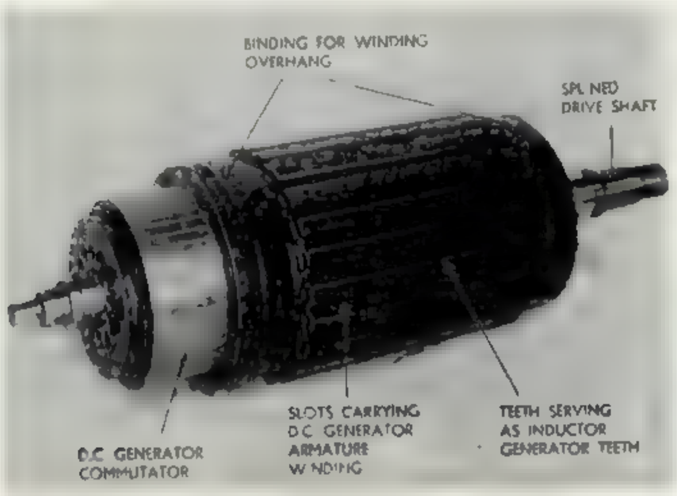


FIG. 6.41. *Rotor of combined d.c. generator and heteropolar inductor generator.*

for aircraft which had been installed with radar equipments, is a combined d.c. generator and inductor generator. This obviated the need for an extra generator mounting pad and provided the relatively modest power requirements with the minimum of modification. Fig. 6.41 shows the rotor and Fig. 6.42 the part-wound stator of a machine of this type which generated 60 amp. at 28 volts d.c. and 15 amp. at 80 volts, 1,150 c/s.

INDUCTION GENERATORS

Induction generators have not been generally used in aircraft but have been used in some missiles as the main generators. In construction they are identical with induction motors and invariably have squirrel-cage rotors. They are attractive because of their simplicity, particularly their freedom from brushes, but their application presents difficulties particularly in the matter of voltage regulation under changing conditions of load and operating speed. A short account of the generator is given here because it has been proposed for future aircraft and is likely to continue to be used in missiles.

Principle of Operation. Operation of an induction machine as a generator

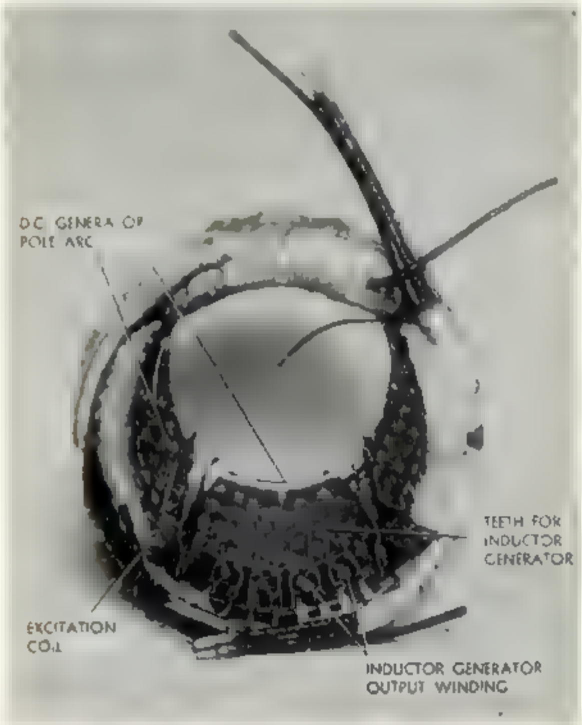


FIG. 6.42. *The stator of the machine shown in Fig. 6.41.*

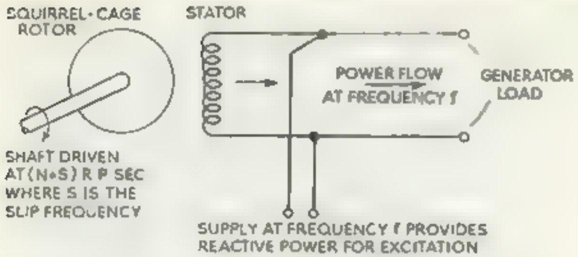


FIG. 6.43. *Induction generator excited from an existing supply.*

can be effected in at least two ways, one requiring an a.c. supply to provide excitation, and another depending on shunt capacitors for this purpose. The former mode of operation is represented in Fig. 6.43 in which the directions of power flow are indicated by arrows. The frequency of the generated power is determined by the frequency of the supply, and the amount of power generated is related to the slip frequency, which is the difference between the rotor speed expressed in r.p.second and the supply frequency. This statement assumes that the stator of the induction generator has a two-pole winding but, if this is not the case, then the rotor speed must be compared with supply frequency divided by the number of pairs of poles. When the machine is generating, the slip is positive and the rotor speed exceeds the supply frequency. Should the slip become negative, the machine receives power from the supply and operates as the familiar induction motor. It should be noted that, whether the machine is generating or motoring, it receives from the supply a magnetizing current which is almost entirely reactive and lagging in phase behind the supply voltage.

Operation independently of a supply requires that a current, equivalent to the magnetizing current, should be established. Since no external voltage is available the magnetizing current must be derived from the source of generated voltage, which is the stator winding of the machine. This is done in very much the same way as a d.c. generator is made to supply its own shunt-field current. Residual magnetism in the induction generator rotor initiates small induced voltages which can give rise to currents if an external circuit is provided between the terminals. The impedance of this circuit, in addition to being low enough to allow the generator to "build up", must be such that the current is correctly phased.

The magnetizing current of an induction motor lags nearly 90 deg. behind the terminal voltage and to secure the same phase relationship between the generator magnetizing current and terminal voltage the external circuit must be capacitive. This may be understood if it is appreciated that a lagging current fed into the machine has the same phase with respect to the terminal voltage as a leading current supplied from the machine. The impedance of the external circuit, like the resistance of the shunt-field circuit of a d.c.

generator, must be below a critical value. Fig. 6.44 (*a*) shows a magnetization curve for an induction generator, and to the same scales a voltage/current curve for a capacitor. Both curves are for a particular speed and the corresponding frequency. The generator terminal voltage and the capacitor voltage must always be identical since the two are connected in parallel as shown in (*b*), and the open-circuit voltage of the generator-capacitor combination, v_{oc}, is given by the intersection of the two curves. The largest value of capacitive reactance which would permit a build-up of generator voltage at this frequency is given by the initial slope of the magnetization curve as indicated by the broken line. Smaller capacitive reactances, (larger capacitors) have voltage/current curves intersecting the magnetization curve at higher voltages, thus by changing the value of the excitation capacitor the open-

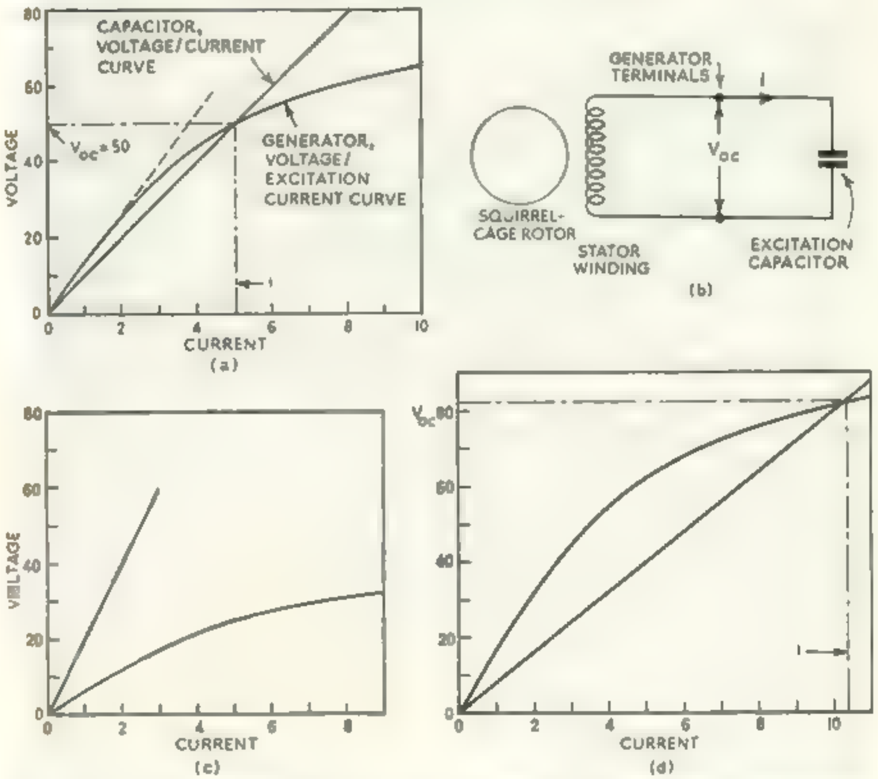


FIG. 6.44. (a) *Magnetization curve for an induction generator and voltage/current curve for a capacitor, superimposed to show open-circuit conditions when connected as shown in* (b); *speed normal;* $V_{oc}=50$ *volts.* (b) *Circuit of self-excited induction generator.* (c) *Curves as in* (a): *speed, half-normal;* $V_{oc}=O$. (d) *Curves as in* (a): *speed* $1\frac{1}{2}$ *times normal;* $V_{oc}=82$ *volts.*

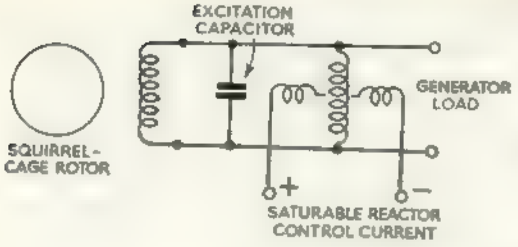


FIG. 6.45. *Circuit of a self-excited induction generator having a saturable reactor for voltage regulation.*

circuit generator voltage can be regulated.

Figs. 6.44 (*a*), (*c*) and (*d*) together illustrate the effects of speed on induction generator operation. The same capacitor value is assumed for each diagram and the speed represented by (*a*) is assumed to be normal. Fig. 6.44 (*c*) shows that excitation will not occur, and it may be inferred by comparing (*a*) and (*c*) that there is a critical speed at which the initial slope of the magnetization curve and the slope of the capacitor curve are identical and at which excitation is just possible.

Voltage Control. The only practicable way of regulating voltage under conditions of changing load and load power-factor is to control the excitation current. Since it is not practicable to change the excitation capacitor directly, an indirect method, such as that shown in Fig. 6.45 is required. In this arrangement the value of excitation capacitor is chosen so that it is large enough to provide the excitation current necessary to maintain rated output voltage under the most arduous load condition. The saturable reactor is adjusted to have a high inductance at this load and a lower inductance at other loads, since current flowing through the saturable reactor is anti-phase to that flowing through the capacitor and only the resultant current is effective in exciting the generator. The weight and size of the saturable reactor depend on the range of the operating load conditions and are generally only tolerable when the load is nearly constant, as is often the case in missiles.

This method of control is also applicable to other a.c. generators but is not generally used

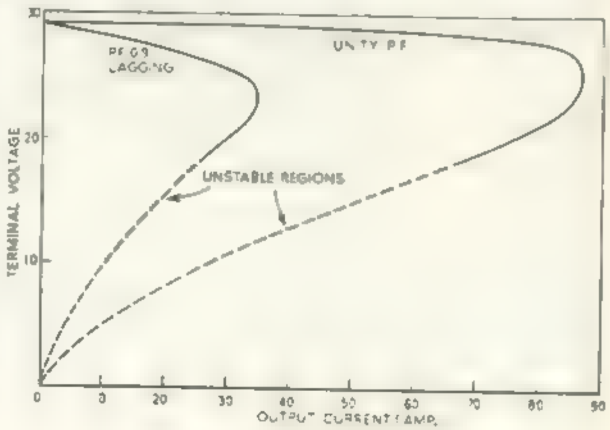


FIG. 6.46. *Load curves for a self-excited induction generator operating at nearly constant speed and with fixed excitation capacitors.*

because of the equipment weight and the losses associated with the control of the saturable reactor and the current flowing in the generator stator windings.

Load Characteristics. Induction-generator load characteristics resemble those of a self-excited d.c. shunt generator as may be seen by comparing Figs 5.2 and 6.46. Like the d.c. generator, the terminal voltage of the induction generator can be made to collapse by overloading. In common with some other a.c. generators, the current available when the generator is short-circuited is not very large and it is still a matter of controversy whether or not it can deliver adequate current into a short-circuit fault to operate protective equipment. The effects of changes of load power-factor are evident from Fig. 6.46 in which the excitation capacitors were unchanged.

CONSTANT-SPEED DRIVES

The degree of accuracy of control of the drive, required to enable a.c. generators to be operated satisfactorily in parallel, is described in Chapter 11. Although any variable-ratio drive could function as a constant-speed drive (C.S.D.), if interposed between an aircraft engine and generator, many available drives are unsuitable. Constant-speed drives of the slipping-clutch type, which were used to give approximately constant speed for some early wind-driven generators, are unsuitable except for generators of less than a few kW rating. This is because such drives have an efficiency which is approximately proportional to the ratio (output speed/input speed), so that at high input speeds the efficiency is low and the heat dissipated at the drive is high. A less conspicuous disadvantage of many drives is that the mechanism for adjusting the drive ratio requires a high operating force or else has a high inertia.

In addition to the variable-ratio gearbox type of drive which derives its power from the shaft of the aircraft main engine, there are drives of the air-turbine type which derive some or all of their power from the main engine compressors and other drives which are independent of the main engines. Each of these types can be operated at constant speed. Air turbines have been the subject of development for several years but have not yet found general acceptance, probably because experience with some units, such as those used on the early Boeing B52 aircraft (Ref. 7) has not been entirely satis-

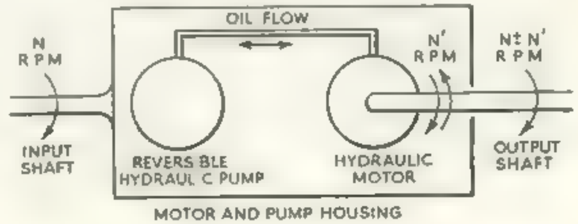


FIG. 6.47. *Illustrating the principle of hydro-mechanical constant-speed drives.*

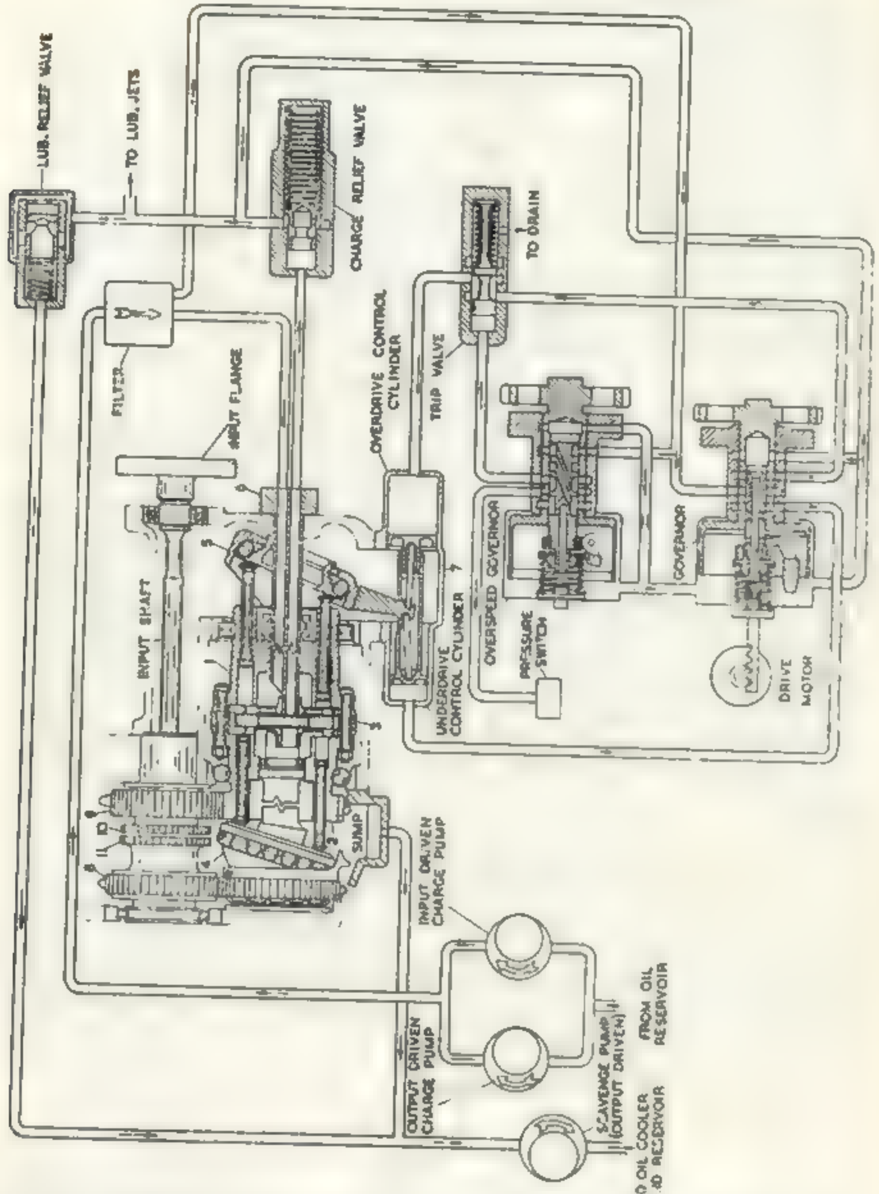


FIG. 6.48. *Sundstrand constant-speed drive: (1) Pump cylinder-block assembly. (2) Motor cylinder-block assembly. (3) Port or valve plate. (4) Motor swash-plate shaft assembly. (5) Pump swash-plate. (6) Manifold assembly. (7) Swash-plate control assembly. (8) Output gear and clutch. (9) Input gear. (10) Input charge pump drive gear. (11) Output drive gear for pumps.*

factory. Independent drives, piston engines and gas turbines, are generally used only where a drive is particularly required when the main engines are inoperative, either in emergencies or on the ground. This is because their fuel consumptions and fuel-to-weight ratios compare unfavourably with those of the main engines.

VARIABLE RATIO DRIVES

A number of mechanical variable ratio drives have been considered but none has yet been generally accepted. These include the Hayes gearbox, used on some pre-1939 British cars, which has been further developed by Tiltman Langley Ltd., and the Beier gear, widely used in Europe as a variable-speed industrial drive and successfully applied in the Napier "Nomad" engine. A description of these units is given in Ref. 8. The most developed variable-ratio drive is of the hydro-mechanical type, some variants of which are described in the following sections. All employ the principle indicated in Fig. 6.47 which shows a hydraulic pump and motor being rotated together by the input shaft. The output shaft rotates at the same speed as the input shaft if the hydraulic motor is locked, but at a greater or lesser speed if the hydraulic motor is operated, depending on the direction of operation of the motor. The principal advantage of this arrangement is that the hydraulic machines are inoperative when the input-shaft speed is equal to the required output-shaft speed. By choosing the gear ratio between the engine and the input shaft it can be arranged that this condition obtains at cruising speed, thereby minimizing wear and losses associated with the hydraulic equipment. Even if this optimum condition cannot be attained, it is evident that a substantial part of the transmitted power can generally be transmitted directly through the drive.

SUNDSTRAND HYDRO-MECHANICAL DRIVE

Principle of Operation. Fig. 6.48 is a diagram showing the essential hydraulic and mechanical components of the drive and their method of interconnexion. Fig. 6.49 shows a cut-away view of the drive in its most common form. Power from the aircraft engine is transmitted from the input flange via the input shaft to the input gears. The driven gear is fixed to the pump and motor cylinder block assembly. This assembly is free to rotate and at one particular value of input-shaft speed will transmit the drive directly to the output gears. At other values of input-shaft speed the mechanism in the cylinder block operates so that the output gear, located at the output end of the block, is driven clockwise or anti-clockwise with respect to the block. The true speed of the output gear is therefore greater or less than that of the cylinder block and the difference is adjusted so that the output speed is of the required constant value.

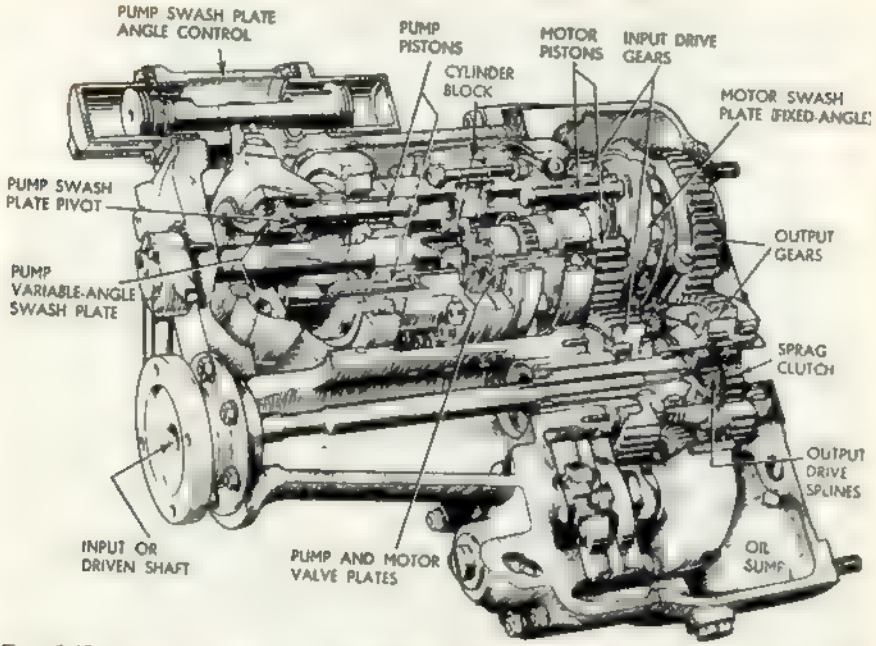


FIG. 6.49. *Cut-away view of a Sundstrand constant-speed drive as manufactured under licence in England by the English Electric Co. Ltd.*

The mechanism of the cylinder block consists of a pump and a motor, each of the swash-plate type employing axial pistons. The pump swash plate is not free to rotate but can be adjusted so that it lies in a plane perpendicular to the cylinder block axis, or is tilted out of this plane in one of two directions. This movement may be understood by referring to Fig. 6.49 which shows the outline of one of the pump swash-plate pivots and the arm by which the angle of tilt of the swash plate is adjusted. When the pump swash plate is perpendicular to the cylinder-block axis, pump pistons bear on the swash plate as the block rotates but do not move axially in their bores. In this condition the pump is inoperative and the hydraulic motor receives no oil input. Owing to the settings of the pump and motor valve plates, the motor pistons are prevented from moving. The drive is therefore transmitted through the cylinder block to the motor swash plate as if the assembly were a single piece.

When the pump swash plate is tilted, as shown in Figs. 6.48 and 6.49, rotation of the cylinder block causes axial movement of the pump pistons and the oil delivered by the pump operates the pistons of the motor. Since the motor swash plate is permanently tilted, the movement of the pistons causes it to rotate, the direction of rotation with respect to the block de-

pending on the direction of tilt of the pump swash plate. Its true speed is, likewise, faster or slower than that of the block. The output drive is taken through gears from the motor swash plate. Built into the output gear is a sprag or wedge-type clutch, serving as a free wheel to allow the output shaft to be driven by the a.c. generator without transmitting power through the drive. This condition could arise if the generator load-sharing arrangements failed or, momentarily, during load or engine-speed changes.

An essential part of the drive is the oil system, partly shown in Fig. 6.48. Oil at about 400 lb. per sq. in. is required to pressurize the cavity in the cylinder block between pump and motor pistons, to maintain contact between the pistons and their respective swash plates. Separation of the pistons from the plates is likely to cause a major mechanical failure. Pressurized oil is also required to power the pump swash plate actuator and over-speed protection device. Oil at a lower pressure is required for lubrication and cooling. The oil is pumped by two gear-type charge pumps from an external reservoir to the cylinder block and also, under control of the governor, to the pump swash plate actuator and to the over-speed device. Leakage past the pump and motor pistons, and the actuator pistons, is collected in the sump. Oil from the cylinder-block cavity is released by the charge relief valve after the cavity pressure has reached 400 lb. per sq. in. and passed to the lubrication jets at a pressure determined by the lubrication relief valve. Excess oil, passing the lubrication relief valve, and oil collected in the sump is pumped by a scavenge pump through an external oil cooler to the reservoir. Two charge pumps are used, one driven from the output shaft and the other from the input shaft, to ensure quick priming and adequate flow under starting and running conditions.

The speed governor on later drives is of mechanical fly-weight type connected directly to a hydraulic spool valve which allows the pressurized oil to operate the pump swash plate actuator in the appropriate direction. Without further elaboration this governor could be expected to maintain an output-drive speed to the required value $\pm$ about 2 per cent. It would, however, not be directly sensitive to the torques being delivered by other drives and could therefore not make any adjustment for unequal load-sharing between generators operating in parallel. Both load-sharing and fine-speed control are effected by the adjustment of the spring setting of the governor with a small a.c. motor which is controlled by the circuits to be described in Chapter 11. This type of governor is illustrated in Fig. 6.48, and both types are described in Chapter 11.

Performance. The Sundstrand drive is at present manufactured in both the U.S.A. and England and there are a number of different sizes and types. The following performance figures relate to the later types, rated at about 50 h.p. output. An output speed of 6,000 r.p.m. and about half the rated

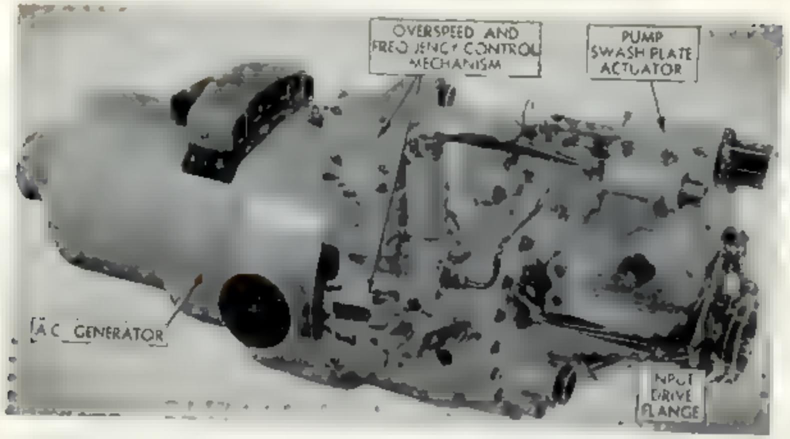


FIG. 6.50. *Sundstrand constant-speed drive fitted with a 40 kVA generator.*

output power can be delivered with an input speed of about 2,700 r.p.m., but the full rated output is not available at input speeds of less than 3,000 to 4,000 r.p.m., depending on the type. Above these speeds overloads of 50 per cent and 100 per cent can be tolerated for periods of 5 minutes and 5 seconds respectively. The highest input speed at which the output speed can be controlled lies between 8,000 and 10,000 r.p.m. Details of speed or frequency control and load-sharing are given in Chapter 11 (see *Frequency Regulation* and *Real Load Sharing*). The full-load efficiency of the drive, taking account of the losses arising from the charge and scavenge pumps, is between 82 and 88 per cent and is highest at an input speed of about 5,000 r.p.m. Assuming 85 per cent efficiency, the losses at a load of 40 h.p. are $40 \times 746 \times (100 - 85)/85 = 5270$ watts. This appears as heat and is mostly carried away in the oil to the external oil cooler. The weight of the oil cooler, oil reservoir and associated pipe lines, air ducts and fittings is estimated at 50 lb. for some installations. Additional penalties arise from the dissipation of heat at such high rates similar to those incurred in the cooling of generators.

Types of Construction. In the form shown in Fig. 6.50 the drive is termed a package-type unit. Other forms, which have been less generally used, include a cartridge unit, which is intended for insertion in an engine accessory gearbox, and a sandwich unit which fits between an engine-drive pad and a generator and has no exposed couplings. Completely separate swash plate pump and motor units have also been considered even though the pump and motor must transmit all the drive power with consequent increased weight and reduced efficiency. The advantages of this arrangement are the saving of space in the immediate vicinity of the engine and the freedom to locate the generators almost anywhere in the aircraft.

OTHER VARIABLE-RATIO HYDRO-MECHANICAL DRIVES

General Electric (*Schenectady, U.S.A.*). This make of drive uses a hydraulic pump and motor having steel balls instead of the more conventional cylindrical pistons. In each case the balls operate in cylinder blocks with radial bores and bear against external races which are eccentric with respect to the cylinder blocks. Changes in the degree of eccentricity have the same effect as changes of swash-plate angle in the Sundstrand drive. The performance of the unit is similar to that of the Sundstrand but it is available in a smaller rating, 9 kVA.

Vickers (*Detroit*). The Vickers drive differs from those previously mentioned in that the hydraulic units, which are standard swash-plate units, receive power from a differential gear at a speed proportional to the difference between input and output shaft speeds.

Slipping Clutch Drive. Labinal (*St. Ouen, France*). This type of drive, called a Variateur, is an eddy-current clutch built integrally with a 4 kVA, 12-pole, 400 c/s generator. It is capable of maintaining a constant output speed of nearly 4,000 r.p.m. under full-load conditions at input speeds between 4,500 and 8,000 r.p.m. The unit, generator and clutch, weighs 38 lb.

Servicing. Hydro-mechanical drives contain a large number of moving parts made to very close tolerances and it is likely that the drives will require overhaul after about 1,000 hours operation. A first cost of about £100 per kVA and an overhaul cost of about one-third of this figure is probable. Lower first costs and cheaper servicing are among the advantages expected of the mechanical drives mentioned under the heading *Variable-ratio Drives*.

BLEED AIR TURBINES

Turbines for aircraft and missile generators, except those powered by ram air, are invariably single-stage impulse turbines and usually operate at 24,000 r.p.m. or higher speeds. Although simple machines, their application using bleed air from aircraft main engine compressors has proved to be difficult. This is mainly because the changing pressure of the air supply has adverse effects on turbine efficiencies. Fig. 6.51 indicates the kind of variations of bleed-air temperature and pressure which occur with altitude under normal cruise conditions. When account is also taken of extreme operating conditions, such as descent with engines idling, it is found that the range of pressures may be as wide as 20 : 1, a ratio which has increased with engine development.

In order to use such an air supply, and to secure a constant-speed generator drive under various generator load conditions, it is necessary to control it. This may be done either by a throttle valve in the supply duct, or by using a turbine having variable-area inlet nozzles, or by a combination of both methods. The throttle valve is simple but causes losses which reduce the

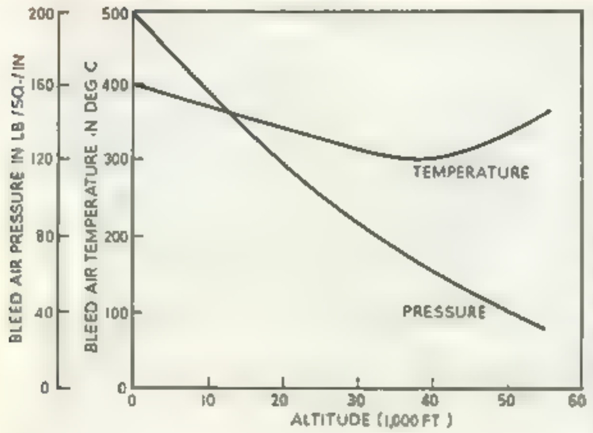


FIG. 6.51. *Curves relating temperature and pressure of engine compressor bleed air with aircraft altitude.*

efficiency of the installation and increase the air flow required from the compressor. Turbines with variable-area inlet nozzles are heavier and more complicated than those having fixed nozzles but are capable of good efficiencies over a range of load and air-supply conditions. It is not certain, however, that the practical range of nozzle area is adequate to deal with extreme conditions of air supply and loading. At very small nozzle areas poor efficiency is to be expected and throttle control may be preferable. Control of nozzle areas is not at easy as control of a throttle valve, and response to changes of load or air-supply conditions is slower.

Conditions of low pressure and temperature are the conditions at which least power is available per unit volume of air, and these conditions—together with the turbine load and efficiency—determine the maximum air flow required. Since the quantity of air available may be limited by deterioration in engine performance, it may be necessary to minimize the air demand by designing the turbine for maximum efficiency at the maximum load and worst air-supply conditions. The maximum generator load is about two or three times full load and occurs only under fault conditions. It is, however, necessary that the generator can meet this in order to provide fault-clearing capacity. A turbine efficiency of at least 70 per cent may be expected at the design condition, but at other air-supply pressures and at normal loads lower efficiencies will occur. Low efficiencies are equivalent to wasted fuel, and the magnitude of this penalty weighs heavily against the use of air turbines.

The practice of bleeding air from the main engine compressor is not considered to be the most economical way of obtaining auxiliary power from an engine, but a precise comparison of the relative effects of extracting 1 h.p. from a shaft, and air of adiabatic head and flow equal to 1 h.p., is not easily made. This is partly because the effects of bleeding air depend very much on the design of the engine and also on the method of controlling engine power. However, even if it is assumed that the adverse effects of the two methods of

extracting power are equivalent, the transmission losses and problems are certainly greater in the case of bleed air.

Ducting for conveying air at 200 lb. per sq. in. and 450 deg. C. in the required quantities is between 2½ and 5 inches in diameter and is lagged with ½-inch glass fibre to minimize the risk of fire and to prevent damage to adjacent equipment and light-alloy structure. The ducts are made of a material, such as stainless steel—which retains its strength at high temperature, in thicknesses of between 0·01 and 0·08 in. Owing to the relative expansion of airframe and ducts, which may be nearly as much as 1 inch in 10 feet, special sliding joints and duct support brackets are required. Early experience brought a number of duct failures some of which have been attributed to resonances in the high-velocity airstream (Ref. 7), and others to an inadequate system of supports and expansion joints. Losses in ducting are caused by heat loss and pressure drop and are estimated at one-fifth of the transmitted power in a typical installation. This loss is large compared with the losses of a mechanical shaft drive, but air ducting permits greater freedom in the location of the generators. It is also possible to connect the air supplies from two or more engines in parallel, thereby making the air turbines independent of any particular engine.

The temperature and pressure ranges given for the air supply in Fig. 6.51 are for air taken from the final stage of a main engine compressor. Bleed is possible from mid-stages at reduced temperature and pressure but, while these reductions would be advantageous at some flight conditions, they would render the supply inadequate under the worst conditions. Mid-stage bleed of quantities adequate for air-turbine drives is difficult to accomplish both because of the limited space between the rows of compressor blades and because successive stages can only be matched properly if the bleed quantity is constant. In two-spool engines interspool bleed is possible without too much difficulty but, as with mid-stage bleed, the air supply may be inadequate under the worst conditions.

Fig. 6.25 shows a unit consisting of an air turbine directly coupled to a 24,000 r.p.m., 400 c/s, 15 kVA generator. The weight of the unit, including control equipment for non-parallel operation, is 130 lb. Cooling of the generator is by circulation of fuel through a heat exchanger which surrounds the generator stator.

Bleed-and-burn Installations. The air demand made by an air turbine may be reduced by burning fuel in the air before passing it to the turbine wheel. An air turbine, modified in this way by the addition of a fuel system and combustion chamber and drawing its air from the main engine compressor, is called a "bleed-and-burn" installation. Except for the compressor it is practically a gas-turbine engine, and the complexity and fire risk associated with such installations are serious disadvantages.

CHAPTER 7

Auxiliary Power Sources

ACCUMULATORS and auxiliary generating plant, although completely different in nearly every respect, can both serve as auxiliary power sources. Each type can be divided functionally into those which constitute part of the main system during normal operation and sometimes contribute to the system performance, and those which are brought into use only in an emergency. The accumulator is naturally suited to d.c. systems whereas the auxiliary generating plant (A.G.P.) is equally capable of providing a.c. or d.c. The earliest, and still by far the most widely used auxiliary source, is the accumulator.

In early aircraft which had small d.c. generators and relatively large accumulators, an accumulator always formed part of the system and contributed to its performance in several ways. Firstly, it functioned as a kind of voltage stabilizer, tending to prevent excessive system voltage by accepting a heavy charging current in the event of a generator operating at excessive voltage, and to prevent low voltages during periods of heavy load by contributing to the load current. A typical load which might be partly supplied in this way is that arising from propeller-blade pitch adjustment. A second function of an accumulator was to provide power before the main engine was started, and during periods when the engine speed was low, such as during taxying and approaches before landing. Thirdly, in the event of failure of all generators the accumulator was capable of supplying all essential electrical equipment for at least 30 minutes, the time considered necessary for effecting a forced landing. Finally, the accumulator was capable of providing power for starting the engines.

On most civil aircraft today the accumulator is still required to be capable of starting one engine, the generator of that engine then providing some of the power for starting the next, but the ratio of generator capacity to accumulator capacity is so much increased that the other functions are performed only to a very limited degree. Military aircraft are, in many cases, equipped with non-electric starters such as cordite or isopropyl-nitrate turbine starters. In both military and civil aircraft the accumulator generally

provides power only for a very limited time while the aircraft is on the ground, or, in emergency, in the air. The voltage stabilizing function is generally ineffective in restraining the system voltage when a generator is operating at excessive voltage, and is not normally necessary for preventing low voltage. The natural characteristic of an accumulator to restrain excessive system voltage by accepting a high charging current, if used for more than a few minutes, has actually proved to be dangerous in modern systems owing to the gassing, and damage suffered by the accumulator.

Accumulators which do not form part of the main power system are usually employed for independent emergency supplies. They are separated from the main system, either to obtain a very reliable emergency source, or because they are of a type requiring special charging arrangements. Extremely reliable emergency sources are required for such things as emergency lights, radio, and firing circuits of explosive bolts which release canopies or escape hatches.

The inability of an accumulator to meet all the requirements of an aircraft on the ground is offset to some extent by the provision of ground supplies which are normally available until the aircraft taxies to the runway. For some military aircraft, supplies are actually provided while the aircraft is waiting on the runway and are arranged to be disconnected automatically as the aircraft moves off. In the event of the failure of all generators in flight, aircraft which have heavily loaded systems can depend on the accumulator only for a few minutes. If the system includes vital electrical loads, such as flying controls, an A.G.P. may be essential.

Auxiliary generating plants find incidental applications such as providing power for main-engine starting, but are usually primarily installed as emergency power sources. In flying boats, which may be required to carry a skeleton crew while moored, an A.G.P. is convenient for providing power for the mooring lights, radio and crew comforts. In aircraft having a.c. systems, an A.G.P. is the alternative to an accumulator and d.c. to a.c. convertor, an arrangement which is very inefficient and not practicable for any except the smallest a.c. systems. In a few aircraft A.G.P's have been integrated with the main electrical system but this is not usual, partly because power is available from the main engines, which invariably operate at better efficiency and at all flight altitudes. Operation of an A.G.P. at take off has the advantage of leaving maximum engine power available for propulsion, and may sometimes be justified.

Generators operated by ram air turbines have recently been developed as emergency power sources. These units, which are normally inoperative, are moved into the slip stream when an emergency supply is required and are descriptively called "pop-out units".

A method of securing an emergency generator drive, in the event of loss

of power of all engines, is to arrange one or more of the engines to "windmill" as the aircraft moves in a downward glide. This is possible both with propeller-driven and pure jet aircraft although it is not certain that adequate drive speed can be obtained under all conditions or with all types of aircraft.

ACCUMULATORS

THERE are several types of accumulator being used in aircraft but the lead-acid accumulator is still the most common. Other types are lighter but because of different charging characteristics, and other differences, they are not direct replacements for the lead-acid type. Testing, evaluation and further development of the newer types is continuing.

Before discussing the various types of accumulators it may be worth while to review the features of accumulators which are undesirable for use in aircraft. Too great a weight and size are always a disadvantage. The need for frequent topping up, cleaning and checking to determine the state of charge increases aircraft servicing time. Removal of the accumulator from the aircraft is often necessary, and it is desirable to provide a way of doing this without carrying the accumulators through passenger compartments. The possibility of electrolyte being spilled, and the presence of spray and corrosive fumes necessitate precautions being taken to avoid corrosion of the aircraft structure. Adequate ventilation must be arranged to remove inflammable gases. These shortcomings have long provided aircraft engineers with jibes with which to chide their electrical colleagues, but the following Sections will show that developments are in progress and that better accumulators may be expected.

LEAD-ACID ACCUMULATORS

The chemistry and construction of the lead-acid accumulator is described in most electrical text-books. Since aircraft accumulators are basically the same as others, only a brief description will be given here. The active materials of the cells are indicated in Table 7.1.

The active materials are formed into plates by pasting them on to grids of lead or an alloy of lead. These grids serve as carriers of the active materials and also as low-resistance paths for current flowing into the plates. Low-resistance grids are particularly necessary for the positive plates because lead dioxide is not a good conductor. This method of construction is adopted in order to build plates of prepared, active materials which do not need forming by initial charging, and also to ensure that the proportion of active material is as high as possible. Other types of plate, such as the Planté plate, in which the active material is electrochemically formed from the pure lead of the original plate, have a lower proportion of active material.

Table 7.1

ACTIVE MATERIALS OF LEAD-ACID CELLS

State of Charge	*Positive Plate*	*Negative Plate*	*Electrolyte*
Charged	PbO_2 (Lead dioxide)	Pb (Lead)	H_2SO_4 Concentrated sulphuric acid
Discharged	$PbSO_4$ (Lead sulphate)	$PbSO_4$ (Lead sulphate)	H_2SO_4 Weak sulphuric acid

Pasted plates for aircraft accumulators have especially thin grids, 0·018 to 0·022 in., in order to obtain a large active surface on a light-weight plate. This is done because the maximum obtainable discharge current, which is usually required for engine starting, increases with plate area. The grid material has, for many years, been an alloy of about 90 per cent lead and 10 per cent antimony, but recent investigations of "battery boiling", which is discussed later, have shown that antimony makes this occur more readily (Ref. 9). Antimony is used for a number of reasons among which is the fact that the alloy is less subject to electrochemical corrosion than pure lead, and also that the alloy has greater strength.

The positive and negative grids are connected by their respective plate straps to terminal posts, and the posts of individual cells are connected by inter-cell connectors. Two points to be noted are, firstly, that in order to minimize resistance, the terminal posts and connectors are usually copper-cored instead of being solid lead and, secondly, that in some of the latest

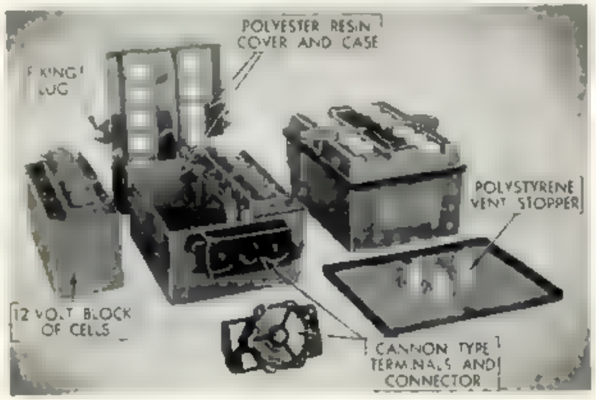


FIG. 7.1. *Lead-acid accumulator of 24 volts, 20 amp.-hr. capacity, which operates without surplus electrolyte.*

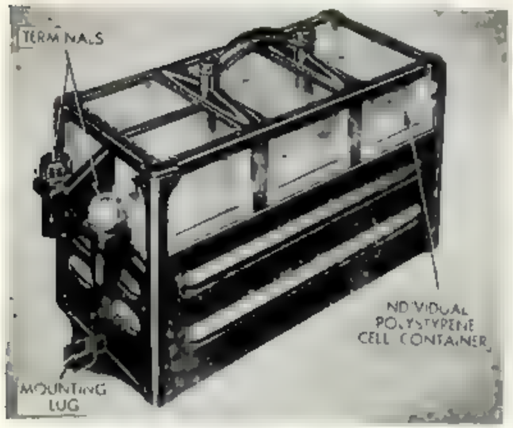


FIG. 7.2. *Lead-acid accumulator of 12 volts, 60 ampere-hour capacity.*

types of accumulator the terminal posts are very short and inter-cell connectors are passed through the cell walls at about the level of the plate straps. This saves weight and effects a small reduction of resistance.

Separators are made of microporous poly-vinyl-chloride (p.v.c.) or a similar material and are made as thin as possible in order to minimize volume. Cell cases are made of polyethylene, now generally known as polythene, or polystyrene, and where the cells are manufactured as individual items or in small batteries or groups, these are housed in an outer case of plastics or metal. Examples of this construction may be seen in Figs 7.1 and 7.2, where the cell cases are polystyrene. The outer case of the Varley accumulator, Fig. 7.1, is a polyester resin reinforced with glass fibre. This accumulator is unusual because the plates are separated by pads of diatomaceous earth, a material chemically similar to sand, and each cell is tightly packed with active plates and separator material. The shedding of active material, either through use or from vibration, is thereby largely prevented. The separators are unusually absorbent and retain all the electrolyte necessary for operation, a feature which permits a reduction in the space above the plates which is normally provided to accommodate electrolyte. The accumulator is rated at 24 volts 20 ampere-hours, at the two-hour rate, and will deliver 130 amp. for 5 minutes before the terminal voltage falls to 16 volts. The weight is 38½ lb.

NICKEL-CADMIUM ACCUMULATORS

The conventional nickel-cadmium accumulator, manufactured in England under the trade name NiFe, has been used in aircraft, but only to a limited extent for low-power applications. This is because it is heavier than the lead-acid accumulator and is not capable of such high discharge currents. The active materials of this accumulator are granular in form and are contained in perforated steel tubes or pockets, groups of which are called pocket plates. This type of plate construction, although mechanically superior to the pasted type of plate used in lead-acid accumulators, since the active

materials cannot be shed, causes high internal resistance which in turn limits the maximum discharge current.

An entirely different method of construction appeared during the second world war in the German Focke-Wulf aircraft and this has been developed to give an accumulator which is superior in performance to the lead-acid accumulator. Both the positive and negative plates are made of sintered nickel, in some types carried on a grid or sheet-steel base, and are processed with nickel hydroxide and cadmium hydroxide respectively. These sintered plates are more robust than pasted plates and have good electrical conductivity. The principal chemical changes occurring in the cell are the same as in conventional nickel-cadmium cells and these are summarized in Table 7.2.

Gassing in this type of accumulator can be totally suppressed during both charge and discharge and totally sealed cells are therefore possible, but at present these are only available with relatively small maximum discharge ratings. With heavy maximum discharge currents a pressure-relief valve is used. In either case the need for topping-up electrolyte is greatly reduced, and contamination by atmospheric carbon dioxide, which in conventional alkaline accumulators necessitates annual changes of the electrolyte, is also greatly reduced. Other advantages of sealing are freedom from corrosive fumes and spray and the spilling of electrolyte. It is interesting to note that sealed cells do not operate under high pressures but that the gases evolved at one plate are electrochemically absorbed at the other.

One sintered-plate accumulator, which has been developed to an advanced stage by S.A.F.T. of France, is rated at 24 volts 35 ampere-hours, at the one-hour rate, and weighs 77 lb. It is capable of a discharge current of 525 amp. for one minute before the terminal voltage falls to 16 volts. This accumulator has a built-in temperature- and charge-limiting device, the

Table 7.2

ACTIVE MATERIALS IN NICKEL-CADMIUM CELLS

State of Charge	*Positive Plate*	*Negative Plate*
Discharged	$Ni(OH)_2$ (Nickel hydroxide)	$Cd(OH)_2$ (Cadmium hydroxide)
Charged	Ni_2O_2 and Ni_2O_3 (Nickel oxides)	(Cd) (Cadmium)

Electrolyte. Potassium hydroxide (KOH) unaffected by state of charge.

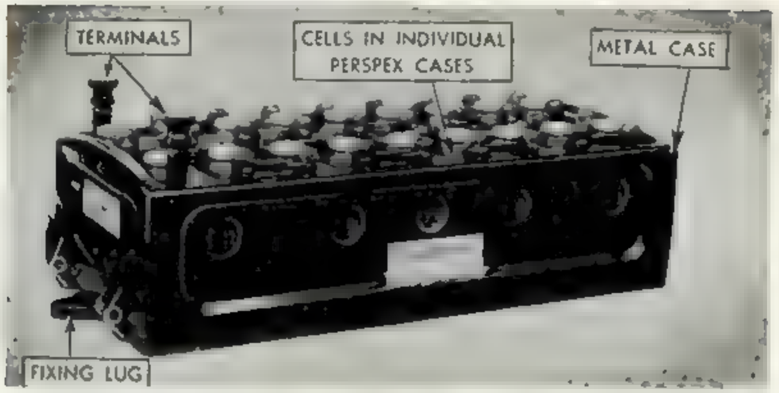


FIG. 7.3. *Silver-zinc accumulator of the type used to provide an emergency supply in B.E.A. "Elizabethan" aircraft.*

purpose of which is explained later. Cells are built in individual steel cases which are carried in a metal crate. The voltage per cell is about 1·4 and 20 cells are required in series to operate in a 28-volt system.

SILVER-ZINC ACCUMULATORS

The outstanding features of this accumulator are its low weight and volume, which are only about a quarter of those of lead-acid accumulators of the same rating. In addition, it is capable of very heavy discharge rates. Early development is attributed to Henri André in Paris and post-war development has been carried out in England by Venner Accumulators Ltd. The essential chemical changes are given in Table 7.3.

Table 7.3

ACTIVE MATERIALS IN SILVER-ZINC CELLS

State of Charge	*Positive Plate*	*Negative Plate*
Discharged	Ag and Ag_2O (Silver and some silver oxide)	ZnO (Zinc oxide)
Charged	AgO and Ag_2O (Silver oxides)	Zn (Zinc)
Electrolyte. Potassium Hydroxide (KOH) practically unaffected by state of charge.		

FIG. 7.4. *Emergency cabin light fed by a silver-zinc accumulator and operated by horizontal decelerations in excess of 2g.*

The two principal disadvantages of this type of accumulator are its short life and difficult charging characteristics. The end of its life is believed to occur as a result of chemical action between the silver oxides and the separator material, which causes a sudden breakdown of the insulation between the plates. This almost invariably occurs towards the end of a charging period and takes the form of a minor eruption which disintegrates the accumulator. An accumulator which has received a full charge and has been standing for about half an hour can be considered safe until the next charge.

Details of the charging characteristics are discussed, together with those of other accumulators in the following paragraphs. Owing to the foregoing difficulties the use of the accumulator is at present restricted mostly to that of a stand-by accumulator which is charged and serviced on the ground. Aircraft which use it as a system accumulator are those with small electrical loads and short operating times, and under these circumstances complete recharging in the air may not be a matter of importance. Fig. 7.3 shows a silver-zinc accumulator which was carried on some B.E.A. "Elizabethan" aircraft. Another smaller accumulator of this type may be seen in the emergency light shown in Fig. 7.4.

CHARGING CHARACTERISTICS

Accumulators may be charged in a number of ways, of which constant-current and constant-voltage charging are two easily defined procedures. These are illustrated in Fig. 7.5.

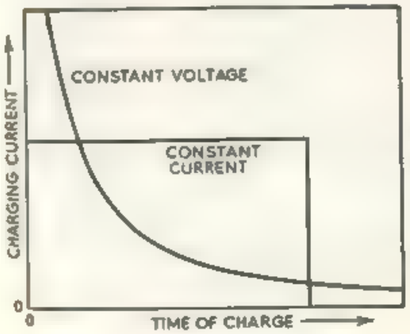


FIG. 7.5. *Two practical charging procedures, constant-voltage and constant-current.*

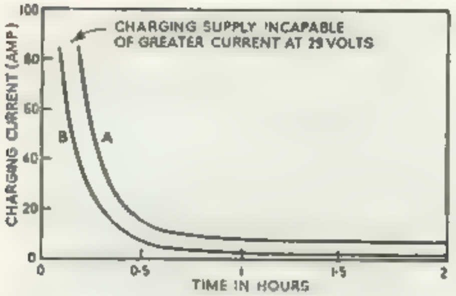


FIG. 7.6. *Charging current/time curves for a lead-acid accumulator charged at constant voltage. Charging voltage, 29 volts (2·42 volts per cell). Ambient temperature, 20 deg. C.* A: *almost fully discharged before recharging.* B: *half-discharged before recharging.*

Since an aircraft d.c. power system operates at a constant voltage it follows that an accumulator connected directly to the system will be charged at constant voltage. The disadvantage of this method is that if the system voltage is exactly the right value to bring the accumulator to a complete state of charge, the charging current occurring at the beginning of the charge is very large and the time taken to complete the charge is very long. Increasing the system voltage hastens the conclusion of the charge and eventually causes overcharging; it also increases the initial charging current to an undesirably high value. Decreasing the voltage alleviates the initial conditions but prohibits the possibility of completing the charge. The lead-acid accumulator can be operated satisfactorily with constant-voltage charging but it is not so practicable for other types.

With constant-current charging it is always possible to select a value of current which will charge an accumulator satisfactorily, although not necessarily in the shortest time. In aircraft, this method would require equipment to determine the state of charge of the accumulator and to control the charging current. Constant-current charging has not been used in aircraft, but for some of the newer types of accumulators the constant-voltage system of charging is modified to limit the current under certain conditions.

Constant-voltage Charging Characteristics. Fig. 7.6 shows charging current/time curves for a 12-cell lead-acid accumulator charged at 29 volts in an ambient temperature of 20 deg. C. The high initial charging currents are seen to be many times greater than the average charging currents, and initial and average currents are increased if the accumulator is initially discharged. Similar curves are obtained with nickel-cadmium sintered-plate and silver-zinc accumulators, but the values of initial charging currents, particularly for silver-zinc, tend to be higher. This is a feature which makes these accumulators less suitable than the lead-acid types for constant-voltage charging.

Fig. 7.7 shows charging current/time curves, two of which illustrate an unstable condition in which charging current increases with time. Since this is both unusual and dangerous it is worth while to examine the conditions under which it occurs. Firstly, the charging voltage is maintained at 29 volts

regardless of the magnitude of the current accepted by the accumulator. Most small charging equipments are incapable of doing this and do not maintain the voltage at the higher currents. Early aircraft generating systems were similarly limited, but modern systems have virtually unlimited capacity. Secondly, the charging voltage, 29 volts, is a little higher than the normal value, 28·5 volts. Finally, the ambient temperatures are a little higher than normal. High ambient temperatures were uncommon in early aircraft, which were of relatively open construction.

In modern aircraft with enclosed fuselages, and in some cases with separate accumulator compartments, high ambient accumulator temperatures have occurred more frequently. Thus some of the conditions necessary to cause instability are more nearly fulfilled in modern aircraft than they were in earlier machines and cases of instability have been occurring over the last decade.

The result of this unstable condition, otherwise known as "battery boiling" or "going into a vicious cycle", if it is allowed to persist, is total destruction of the accumulator. The increasing charging current causes a rapid temperature rise and boiling of the electrolyte. The high temperature softens the cell cases and distorts the plates, which in turn distort the cases. The boiling electrolyte, together with volumes of hydrogen and oxygen from electrolysed water, emerge from the cells until they are dry. These gases are in the correct proportions to recombine violently if ignited.

Ignition from within the cells, from short-circuiting between the plates, is unlikely but has been known to occur. Ignition of the gaseous mixture outside the accumulator but in the confined spaces of the aircraft is also possible. These dangers, together with the damaging effects of corrosive acid fumes, are good reasons for ensuring that this phenomenon does not occur in an aircraft. At high altitudes, where reduced atmospheric pressure reduces boiling temperatures, it is possible for an accumulator to "boil"

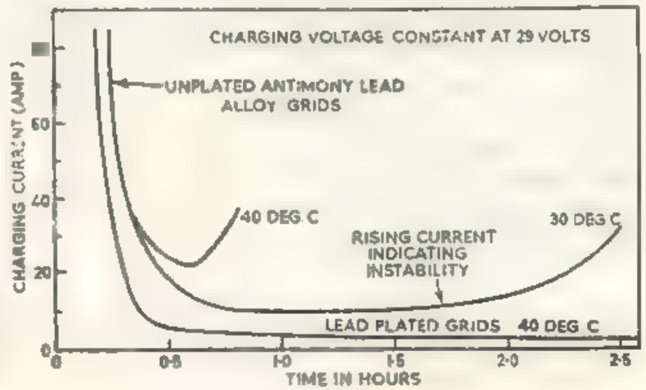


FIG. 7.7. *Constant-voltage charging curves for lead-acid accumulators with plated and unplated grids.*

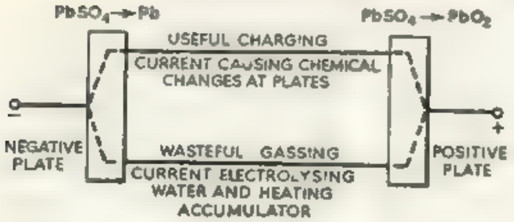


FIG. 7.8. *Diagram showing useful and wasteful components of charging current.*

without being raised to a damagingly high temperature. This is still extremely dangerous. It may leave only corrosive deposits in the aircraft and a dry accumulator as evidence and can be mistaken as a case of spilt electrolyte or bad servicing.

An interesting indication of the progress which is being made towards greater stability is given in Fig. 7.7 which shows charging current/time curves for two lead-acid accumulators which were identical except that one had lead-plated grids instead of the standard lead-antimony alloy grids. To understand the effectiveness of lead plating it is necessary to consider Fig. 7.8 which shows the charging current as two parallel currents having different effects. The true charging current causes chemical changes at the plates and generates only a little waste heat. The other current is entirely wasteful and causes the electrolysis of water and generates much more waste heat than the charging current. This "gassing current" increases with temperature so that if the heat it generates is retained by the accumulator, a cumulative effect of rising temperature and increasing gassing current can result. Instability therefore appears to be possible in any accumulator which is charged at excessive voltage and allowed to attain an excessive temperature.

Antimony from the alloy grids is transferred in small quantities to the negative plates, where it reduces the voltage necessary for the release of hydrogen. Thus the gassing current is greater in cells with exposed antimony-alloy grids and the critical condition, when the heat produced by the combined currents exceeds that lost by the accumulator, is reached more easily. An alternative to lead-plated grids is the use of alloys such as lead and calcium.

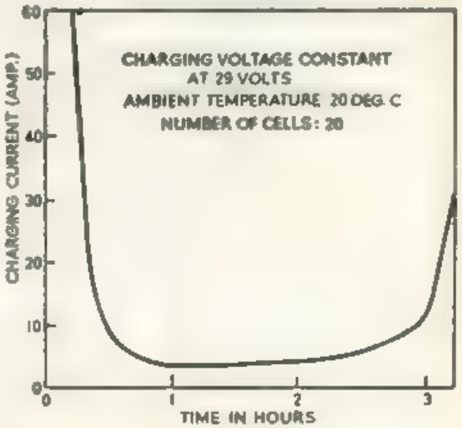
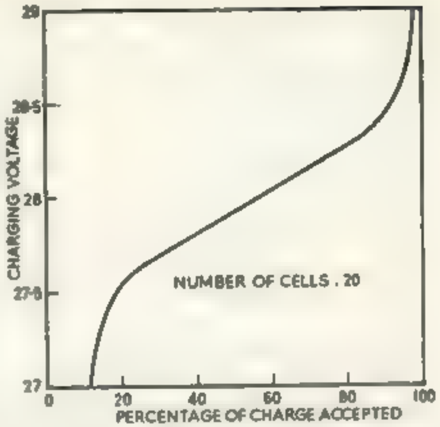


FIG. 7.9. *Instability in a sintered-plate nickel-cadmium accumulator.*

FIG. 7.10. *Showing the amount of charge accepted by a sintered-plate nickel-cadmium accumulator over a range of constant charging voltages.*



Instability in a sealed nickel-cadmium accumulator with sintered plates is illustrated in Fig. 7.9. This type of accumulator tends to be slightly less stable than the lead-acid types. It shows the greatest tendency to instability when recharged after partial but not complete discharge, whereas a lead-acid accumulator is most sensitive after complete discharge. In some of the S.A.F.T. sintered-plate nickel-cadmium accumulators instability is checked by fitting a temperature-sensitive relay to the accumulator, which switches off the charging current in the event of excessive temperature rise but does not interfere with discharge current.

The best voltage for charging 12-cell lead-acid accumulators is between 28 and 28·5 volts; 29 volts is high enough to cause instability and at lower voltages the accumulator cannot be completely charged. At 27 volts only about 75 per cent charge is possible. Sintered-plate nickel-cadmium and silver-zinc accumulators require even more precisely controlled charging voltages as is indicated by Figs. 7.10 and 7.11. From Fig. 7.10 it can be seen that 29 volts is required by the nickel-cadmium accumulator for complete charging, but from Fig. 7.9 it is known that this voltage is sufficient to cause instability. These facts confirm the need for a temperature-sensitive relay to control the charging current if the accumulator is charged from a constant-voltage supply.

A peculiar effect, which might be confused with "battery boiling",

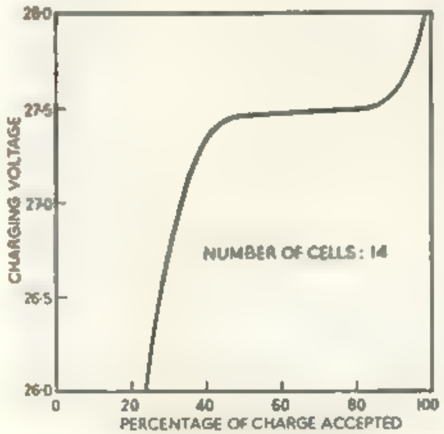


FIG. 7.11. *Showing amount of charge accepted by a silver-zinc accumulator over a range of charging voltages.*

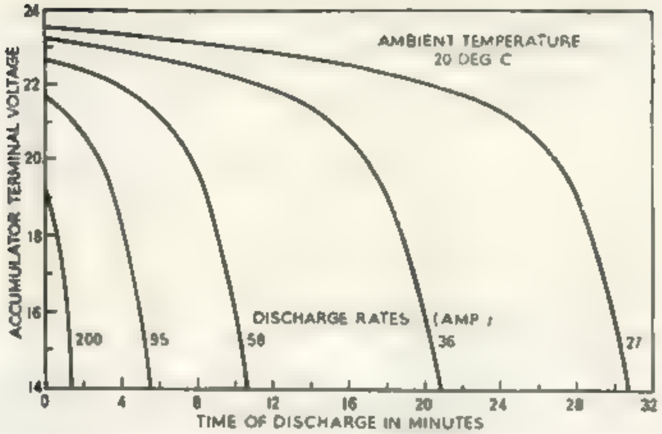


FIG. 7.12 *Discharge curves for a 12-cell lead-acid accumulator rated at 25 ampere-hours at the 10-hour rate.*

is the apparent disappearance of the electrolyte—sometimes observed after high-altitude flying. The electrolyte reappears about an hour later! The explanation is that at high altitude, where atmospheric pressure is low, gas which is normally present in the accumulator plates is released and its place is taken by electrolyte. On returning to sea level the electrolyte is slowly expelled from the plates by newly formed gas and the electrolyte level is restored.

DISCHARGE CHARACTERISTICS

A set of terminal voltage/time curves for a lead-acid accumulator, discharged at several different rates, is shown in Fig. 7.12. These illustrate several things common to all types of accumulators. Firstly, the initial terminal voltage is reduced as the rate of discharge is increased. This is mainly because the accumulator has internal resistance, and is one of the reasons for designing low-resistance inter-cell connectors and plates with active materials in good electrical contact with the grid or base. Secondly, the curves show a steady fall of voltage as the discharge proceeds. This is caused by such things as weakening of the electrolyte in the vicinity of the active materials and by chemical changes or discharging of those particles of active material offering the lowest resistance paths. Sintered-plate nickel-cadmium cells have similar discharge curves to those of lead-acid cells, but silver-zinc accumulators have discharge curves which are exceptionally flat, the voltage falling away suddenly at the end of discharge. Fig. 7.13 is derived from 7.12 and shows that the energy available is much reduced at high discharge rates. This is true for all types of accumulators and shows that when

used for such applications as engine starting, they are being used in the least favourable way.

Although at normal discharge rates the sintered-plate nickel-cadmium accumulator is only a little superior to the lead-acid accumulator (compared on a weight basis) at high discharge rates when the discharge current is, say, ten times the rating of the accumulator in ampere-hours, it performs very much better than the lead-acid types. Its duration may be twice as long and the falling-off in voltage during discharge, less severe. Silver-zinc accumulators, which may have as much as four times the capacity of lead-acid accumulators of the same weight at normal rates of discharge, are also good performers at high rates.

The discharge performance of all accumulators is adversely affected by low temperature. Initial on-load voltages are slightly reduced, duration and rate of fall of voltage are more seriously affected, all the effects being appreciable at temperatures of less than about 0 deg. C. Alkaline cells (sintered-plate nickel-cadmium and silver-zinc) tend to be unreliable at low temperatures. They are much more sensitive to chemical impurities than are lead-acid cells and it is probable that improved manufacturing techniques may lead to better low-temperature performance.

One method of obtaining large outputs at low temperatures is to fit a heating element which requires a relatively small amount of power and raises the accumulator to a temperature at which it can perform its main function. The silver-zinc accumulator, with its very high stored-energy/weight ratio is well suited for this technique. At very low temperatures, perhaps less than −40 deg. C., it may be impracticable to obtain even sufficient power to supply a self-heating element. Unaided, the lead-acid accumulator appears to be the best low-temperature accumulator. Low-temperature performance is particularly important to aircraft operating in cold climates and using electric starters. It may also be important for emergency accumulators in high-altitude aircraft, but in use, accumulators are usually adequately self-heating.

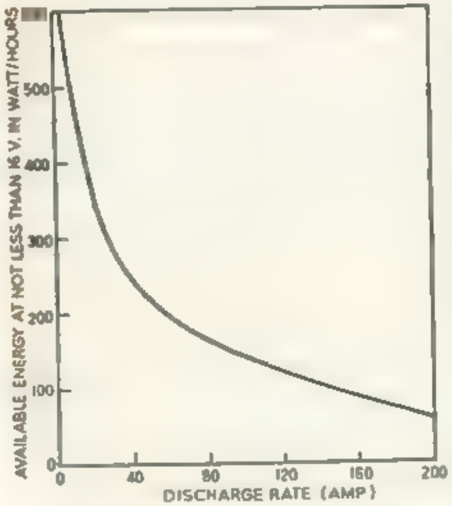


FIG. 7.13. *Curve relating available energy and discharge rate for a lead-acid accumulator. Nominal voltage, 24 volts.*

SHORT-DURATION RESERVE CELLS

Cells which are capable of providing large powers for a short length of time have already found applications in missiles, where flight times are measured only in minutes, and are a possible emergency power supply in aircraft. Conventional primary cells are not capable of very high discharge rates and generally have a storage life of less than 12 months. Also it is usually impracticable to prove their condition without completely discharging them, and this uncertainty makes frequent replacement necessary. The accumulators discussed in the previous sections are not ideal as emergency supplies because they are not capable of standing for more than about two weeks in the charged condition without appreciable loss of charge. Servicing is therefore necessary.

Several types of accumulator can be made so that, when filled with electrolyte, they are in the fully charged condition ready for immediate discharge. Generally, life and charging characteristics are unimportant in short-duration reserve (S.D.R.) cells and the silver-zinc type is an obvious choice because of its high energy/weight ratio. The mechanism for filling a battery of cells with electrolyte, automatically and quickly, has been the subject of some development and dependable methods are now available. Unfortunately, the separate storage of electrolyte and the filling mechanism add to the weight and size.

Fused-electrolyte Cells. These cells, otherwise known as thermal cells, use an electrolyte which is solid at normal temperatures. They are completely inactive until the electrolyte is fused and consequently have an exceptionally good storage life. A practical cell can be made with potassium chloride as the electrolyte and calcium and nickel electrodes. The electrolyte can be melted by surrounding the cells with a slow-burning compound, similar to that used for vulcanizing patches on to automobile tyre tubes; the compound can be ignited by a small heating element. The duration of the output of these cells depends primarily on the length of time for which the electrolyte can be maintained above its melting point. Activation can be effected in less than a minute and with thermal lagging a duration of 10 minutes is practicable. The energy/weight ratio is inferior to that of the silver-zinc S.D.R. cell but it is much more robust and capable of activation at lower temperatures.

AUXILIARY GENERATING PLANTS

AUXILIARY generating plants almost invariably employ gas-turbine units because this type of prime mover is lighter than the equivalent piston engine, and because it is well suited to deliver large quantities of air at pressures between 40 and 60 lb. per sq. in. absolute so that it can be used for starting the main engines. Like air turbines, they operate most efficiently at high

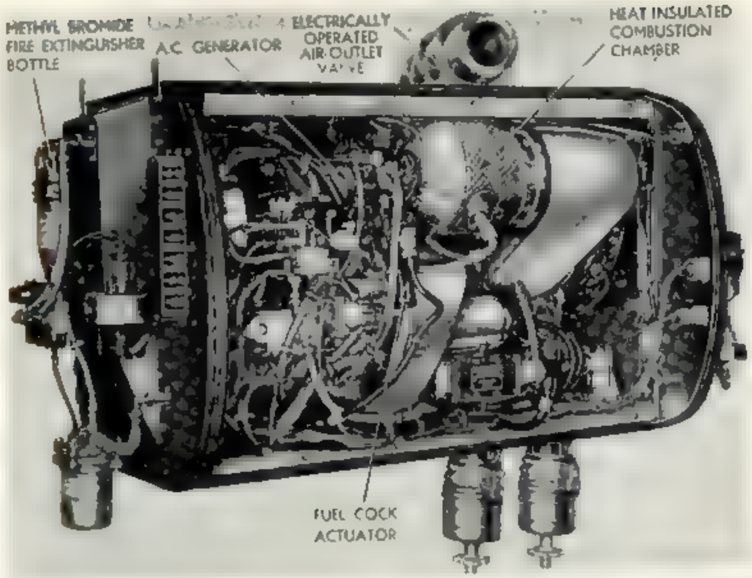


FIG. 7.14. *Auxiliary generating plant powered by a gas-turbine engine and providing 32 kW, three-phase power, or compressed air. Weight 400 lb. Dimensions, 53 × 38 × 24 in. Specific fuel consumption 1·4 lb. per b.h.p. per hour at the turbine shaft.*

speeds and are best suited to drive high-speed a.c. generators. Present development is aimed particularly at lower specific fuel consumption and better high-altitude starting and performance. At altitudes greater than 30,000 or 40,000 feet difficulty may be experienced with starting, but if running, some power may be obtainable up to about 50,000 feet. High-altitude performance may be improved by using ram air to assist the compressor or by bleeding the main engine compressors. The former depends on forward air speed and incurs drag losses, and the latter may be undesirable because of its effect on main engine performance, which was discussed in Chapter 6 (see *Bleed Air Turbines*).

Fig. 7.14 shows a gas-turbine A.G.P. which is being fitted to some Avro "Vulcan" aircraft to provide compressed air and electrical power. At sea level it can deliver 550 cu. ft. of air per minute at 44 lb. per sq. in. absolute, in an ambient temperature of 15 deg. C. Its maximum electrical output is 32 kW, which can be delivered at up to 10,000 ft. Derating its necessary at higher altitudes, the present state of development allowing 15 kW at 30,000 ft. The unit was intended to provide low-pressure air for engine starting and emergency electrical power in flight; maximum electrical and pneumatic outputs cannot be obtained simultaneously.

The A.G.P. incorporates both electrical and cordite cartridge starters.

The latter method is necessary for starting at altitude but also reduces the starting period from 30 to 5 seconds. A thermostatically controlled three-phase heater is provided for the lubricating oil to facilitate starting in the low ambient temperatures experienced at altitude. Other electrical accessories include 28-volt actuators for operating the oil-cooler flaps and fuel cock.

Fig. 7.15 shows a similar unit of somewhat higher power rating. It has been installed on some Canadair C.L.44 transport aircraft and provides, in addition to electrical and pneumatic power, hydraulic power for operating the freight doors. Turbine speeds of the two units are 46,000 and 35,000 r.p.m. respectively.

Piston-engined A.G.P's have been used in many different aircraft but were never accepted as enthusiastically as were the gas-turbine units. In early aircraft they were sometimes used to generate power for radio equipment; during the second world war they were occasionally used to supplement the main generators and as emergency power sources, and not infrequently they have been used to provide power for experimental and development work. In the latter case work may proceed with greater freedom because the main electrical system is not jeopardized.

Emergency Ram Turbo-generator Units. These units are normally contained in the lower part of the fuselage of an aircraft and are extended into the slip stream when required. They have been generally called "drop-out units" and "pop-out units", the latter name having been applied mostly to the smaller units which appeared in the early 1950's. Most units, like the one shown in Fig. 7.16, consist of an axial-flow turbine directly coupled to

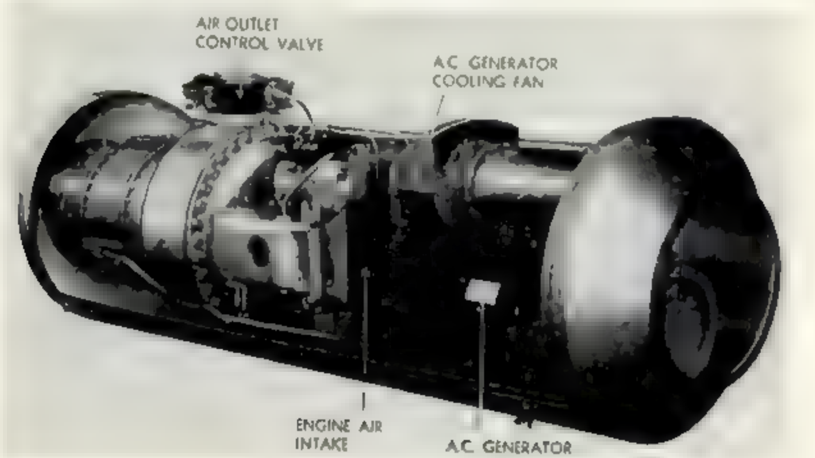
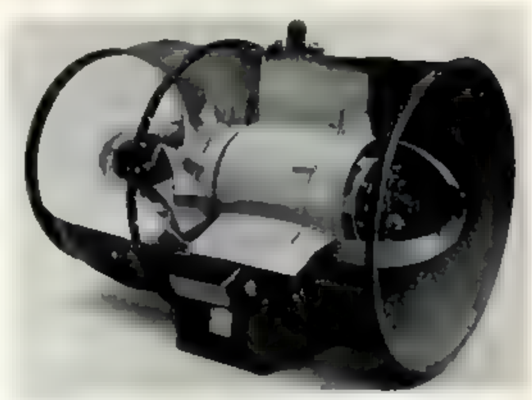


FIG. 7.15. *Gas-turbine auxiliary generating plant using a Blackburn-Turbomeca "Artouste 510" engine.*

FIG. 7.16. *Ram air emergency generating unit having an output of 15 kVA. The cooling air enters at the left and is expelled at the right. The turbine blades are of variable pitch, and the pitch-change mechanism is contained in the centre nacelle.*



an a.c. generator. The generators have not been intended for parallel operation with other generators, in consequence, control of turbine speeds and torques has not been developed to particularly close limits. The unit illustrated is controlled to within 5 per cent of the nominal speed under steady-state conditions. The speed-control system uses a centrifugal governor which operates directly to adjust the pitch of the turbine blades. An alternative method of speed control, giving control to within similar limits, uses a governor operating to adjust the angle of the inlet guide vanes. A unit employing this principle has been developed by the Plessey Company and proved at speeds up to about 700 m.p.h.

Voltage control is by normal methods and is achieved to within 2 per cent of the nominal value under steady-state conditions. It is generally necessary to have a method of initial excitation which is independent of other aircraft supplies. The a.c. generator of the unit shown in Fig. 7.16 has a permanent-magnet, rotating-field a.c. generator of 150 VA rating (built within the frame of the main 15 kVA generator) which can be used for excitation purposes.

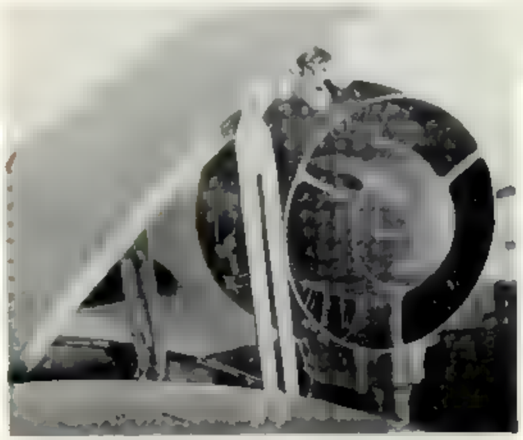


FIG. 7.17. *Ram air emergency generating unit shown in the "dropped-out" position.*

CHAPTER 8

Power-Converting Equipment

THE elimination of power-converting equipment from aircraft power systems is a desirable objective, firstly to achieve simplicity, secondly, because of its weight and size, and thirdly because of its low efficiency. However, at present it is not possible to design a competitive system without recourse to some equipment which is installed, primarily, to convert electrical power from one form to another. This is because many different types of utilization equipment are installed, requiring different kinds of power supply. The use of different kinds of supply is almost unavoidable. For example, small brush-less motors used in such instruments as auto-pilot gyroscopes require a polyphase supply, whereas small relays are most satisfactorily designed for low-voltage direct current.

To build-in power-converting equipment to each item of utilization equipment is possible, but is generally uneconomical compared with the provision of converting equipment which provides a supply for several items. Thus, most aircraft carry convertors to provide those standard supplies which are not provided by the main generators. Standard supplies are listed here. The order of listing is of no significance but supplies (*d*) and (*e*) are rarely provided by main generators: (*a*) 28 volts, d.c.; (*b*) 112 volts, d.c.; (*c*) 200 volts, a.c. three-phase, 400 c/s; (*d*) 115 volts, a.c. three-phase, 400 c/s; (*e*) 115 volts, a.c. single-phase, 1,600 c/s. (Note. Three-phase voltages are measured between lines).

Power conversion may be between any of the standard supplies or from a standard to a non-standard supply. In some cases it may only involve a change in the quality of the supply, such as from a supply which is regulated to within $\pm$ 2 per cent of a particular voltage to one which is regulated to within $\pm\frac{1}{2}$ per cent, or from one containing harmonics or electrical noise to one which is relatively pure. The equipment divides conveniently into two types, rotating and static.

Generally, any converting function can be performed by either type, but the economical fields of application of each type are fairly clearly defined.

ROTATING MACHINES AS CONVERTORS

THERE are several converting functions for which rotating machines are unequalled despite the disadvantage that they require more servicing than do static equipments. In d.c. aircraft (aircraft having d.c. main generators) the conversion of d.c. power of more than a few watts, either to a.c. or from one voltage to another, has been a long established role for these machines. In a.c. aircraft the conversion of frequency of all except very small powers is effected by rotating machines, but most other converting functions are achieved by static equipment. Efficiencies of rotating convertors are rarely higher than 50 per cent and specific weights are between 20 and 50 lb. per kilowatt output for most machines having outputs greater than about 200 watts. Smaller machines generally have much lower efficiencies and higher specific weights.

Some uncertainty exists as to the correct name for each type of converting machine. It is not proposed to justify the nomenclature used here but care is taken to define each type named. All types are referred to as converting machines or rotating convertors and individual types are named by virtue of their construction rather than by their function. The term "inverter", which is not adopted here, is generally given to machines which convert d.c. to a.c. regardless of their type of construction.

MOTOR-GENERATORS

Motor-generators consist of a driving motor coupled mechanically to one or more generators, and each machine is electrically and magnetically separate. Other types of rotating convertors are usually lighter but these are the simplest, most adaptable and most easily controlled. The motor is usually a d.c. motor operated from one of the standard voltages. If the motor drives an a.c. generator its frequency may be precisely regulated by controlling the d.c. motor field current, but if the frequency is not very critical the motor may be fitted with differential series windings to secure approximately constant speed with changing load. Output voltage, whether a.c. or d.c., may be regulated by controlling the generator field current. Output and input voltages are not related as in some types of convertors and the motor-generator can be designed for a wide range of values. Output voltages in excess of 1,000 have been used for radio supplies.

To minimize weight, the motor and generator are usually built in-line and on a common shaft, and share a single frame. This form of construction tends to give a long machine which may be difficult to cool and have an undesirably long distance between the shaft bearings. Radio interference, arising at the brushes, requires external suppressors or filters. With this machine, since there is very little mutual inductance between motor and

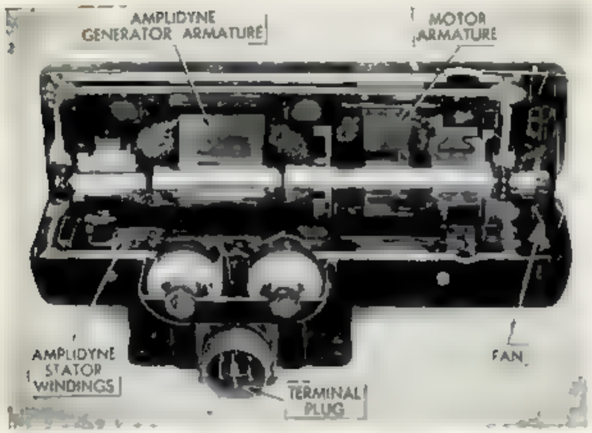


FIG. 8.1. *Motor-generator used for powering gun-turret drive motors.*

generator windings, ripple voltages arising at the motor commutator are not likely to be transferred from input to output.

Fig. 8.1 shows a motor-generator made in the U.S.A. for supplying controlled power to the gun-turret drive motors of the wartime Super Fortresses. This machine has a 28-volt d.c. six-pole motor and an amplidyne generator, the maximum output of which is 60 volts, 8·8 amp. for 10 minutes. An amplidyne may be regarded as a d.c. generator designed primarily as a power amplifier, the excitation power being the input quantity. The machine has a light-alloy frame and two end plates, each of which houses one of the shaft bearings. Overhanging the bearing at the motor end is a centrifugal fan which draws air through the length of the machine and also on to the motor commutator via four subsidiary inlets. The speed of the machine is not controlled and is about 8,300 r.p.m. The weight is 29 lb. Some information about the application of this machine is given in Ref. 24, and amplidyne theory in Ref. 25.

A motor-generator having two a.c. generators is shown in Figs. 8.2 and 8.3. One

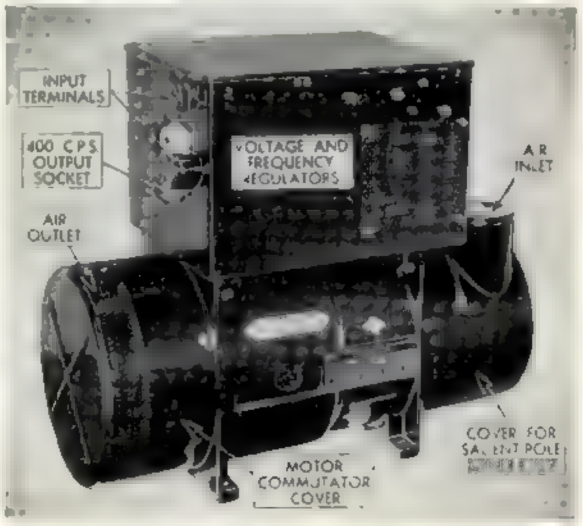
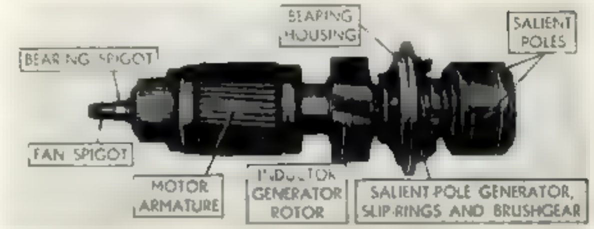


FIG. 8.2. *Motor-generator with control unit, providing regulated 400 c/s and 1,000 c/s outputs.*

FIG. 8.3. *Rotor of the motor-generator shown in Fig. 8.2.*



generator of the inductor type provides 1 kW of 1,600 c/s power, and another of the salient-pole rotating-field type provides 2 kW of 400 c/s power at 115 volts. To minimize the distance between bearings, the salient-pole rotor and its slip-rings are overhung at one end and the cooling fan is overhung at the other. The large control unit mounted on the machine regulates the frequency of both outputs by controlling the motor field and hence the speed. The voltages of each output are individually regulated by controlling the excitations of the a.c. generators. Magnetic amplifiers are used in the control circuits. The weight of the machine is 61½ lb. and the control unit 28½ lb.

ROTARY CONVERTORS

The conventional rotary convertor having a common armature winding brought out to both a commutator and slip-rings, and running in a common magnetic field, has found little application in aircraft. The advantage of reduced copper weight, made possible by the partial cancelling of the direct and alternating currents in the armature, is outweighed by the restriction of an inherently fixed ratio between input and output voltages. Nearly all aircraft a.c. requirements are for voltages higher than those obtainable from rotary convertors powered from either of the standard d.c. supplies. An exception is shown in Fig. 8.4, a convertor with a single-phase output of 19 volts r.m.s.

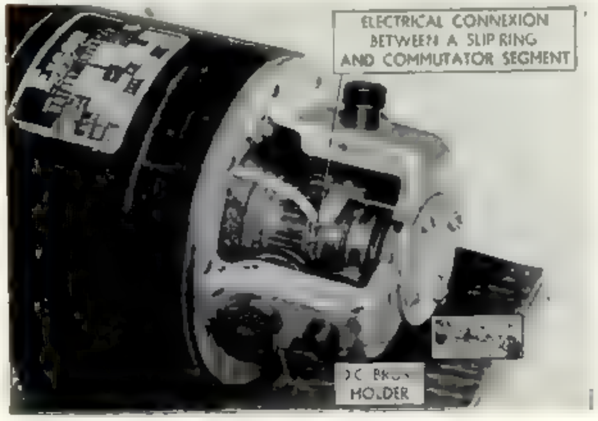


FIG. 8.4. *Small conventional rotary convertor for use in aircraft. The end cover is removed to expose the brushgear.*

ROTARY TRANSFORMERS

A rotary transformer has electrically separate input and output windings wound on a common armature core and running in a common magnetic field. It is extensively used in aircraft for converting standard d.c. supplies to higher voltages and to a.c. As it is not widely used elsewhere its characteristics will be discussed in detail. Consider a machine having one input winding and two output windings all of which are brought out to separate commutators. The input voltage, v_1 is given by

$$v_1 = e_1 + i_1 r_1 \tag{20}$$

where e is the generated or back e.m.f.; i is the current; r is the resistance of the armature winding including the brushes etc.; and subscript 1 refers to the input winding. The effects of armature reaction have been neglected in forming equation 20 and this omission will be justified later. Similar equations may be written for the output voltages, v_2 and v_3:

$$v_2 = e_2 - i_2 r_2 \tag{21}$$

and $$v_3 = e_3 - i_3 r_3 \tag{22}$$

where subscripts 2 and 3 refer to the output windings. Since all windings rotate at the same speed in the same magnetic field

$$e_1 = K_1 n\phi;\ e_2 = K_2 n\phi;\ \text{and}\ e_3 = K_3 n\phi \tag{23}$$

where K is a constant depending on the number of turns and method of connexion of the armature windings; n is the speed in revolutions per second; and ϕ is the magnetic flux crossing the airgap. Substituting for e from equation (23) in equations (20), (21) and (22) gives:

$$v_1 = K_1 n\phi + i_1 r_1 \tag{24}$$

$$v_2 = K_2 n\phi - i_2 r_2 \tag{25}$$

$$v_3 = K_3 n\phi - i_3 r_3 \tag{26}$$

We also know that input and output powers must be equal, so:

$$v_1 i_1 = v_1 i_0 + e_2 i_2 + e_3 i_3 \tag{27}$$

where i_0 is the current taken by the machine running on no load. Dividing equation (27) by v_1 gives:

$$i_1 = i_0 + \frac{e_2 i_2}{v_1} + \frac{e_3 i_3}{v_1} \tag{28}$$

Now, rearranging equation (24) gives:

$$n = \frac{v_1 - i_1 r_1}{K_1 \phi} \tag{29}$$

and substituting for i_1 from equation (28) gives:

$$n = \frac{v_1 - \left\{ i_0 + \frac{e_2 i_2}{v_1} + \frac{e_3 i_3}{v_1} \right\} r_1}{K_1 \phi}$$

Now if we substitute this expression for n in equations (25) and (26) we shall obtain expressions for the output voltages, v_2 and v_3, which show some

interesting characteristics of the rotary transformer. Firstly, substituting for n in equation (25) gives:

$$v_2 = \frac{K_2 \phi}{K_1 \phi} \left\{ v_1 - i_0 r_1 - \frac{e_2 i_2 r_1}{v_1} - \frac{e_3 i_3 r_1}{v_1} \right\} - i_2 r_2$$

$$= \frac{K_2}{K_1}(v_1 - i_0 r_1) - i_2\left(r_2 + \frac{K_2 e_2 r_1}{K_1 v_1}\right) - i_3 \frac{K_2 e_3 r_1}{K_1 v_1} \tag{30}$$

Similarly $$v_3 = \frac{K_3}{K_1}(v_1 - i_0 r_1) - i_3\left(r_3 + \frac{K_3 e_3 r_1}{K_1 v_1}\right) - i_2 \frac{K_3 e_2 r_1}{K_1 v_1} \tag{31}$$

It may be seen that equations (30) and (31) are identical except for the interchange of subscripts 2 and 3.

The first term on the right-hand side of equation (30) gives the value of the output voltage, v_2, when the machine is on no-load and i_2 and i_3 are zero. Since the ratio K_2/K_1 depends on the design of the armature windings alone, v_2 can have any value independent of the value of the input voltage, v_1. The voltage-drop term $i_0 r_1$ is generally small compared with v_1 and only reduces the value of v_2 slightly below the value indicated by the design of the armature windings $(K_2/K_1)v_1$.

The second term shows that the magnitude of the effect of output current, i_2, on the output voltage, v_2, depends on the resistances (r_1 and r_2) of both the input and output windings. The third term shows that the output voltage, v_2, is affected by current, i_3, in the other output winding, the effect being proportional to the input-winding resistance, r_1. Thus, this resistance, which appears in the three right-hand terms of equation (30), slightly reduces the no-load value of v_2, increases its regulation under load, and causes interaction between the two outputs. Its value should therefore generally be low. From this discussion it might appear that the inherent regulation of a rotary transformer is greater than that of a d.c. generator, but this is not necessarily so. The tendency of the combined effects of input- and output-winding resistances, to give high or bad regulation is offset by the fact that in a rotary transformer the armature reaction m.m.fs. of the input and output currents are approximately equal and nearly cancel. Thus, armature-reaction effects are small, and the regulation of v_2 is determined almost entirely by the term $i_2(r_2 + K_2 e_2 r_1 / K_1 v_1)$. Also because of this, commutation is generally good and interpoles are not usually fitted. Machines having an a.c. output are sometimes at a disadvantage because the a.c. and d.c. windings require different numbers of slots. This necessitates the use of dummy coils in the d.c. winding and these can cause some instability of commutation. High mutual inductance between each of the armature windings is inherent in the construction and is sometimes a disadvantage since commutation ripple and electrical noise arising in any one circuit inevitably appear in the others.

It is interesting to notice that the no-load value of the output voltage, v_2, is related to the input voltage by the ratio K_2/K_1, which is analogous to

the turns ratio of a static transformer. Analogy between rotary and static transformers is also to be found in the second term on the right-hand side of equation (30), where the term $K_2 e_2 r_1 / K_1 v_1$ gives the effective value of primary resistance, r_1, referred to the secondary circuit. This term simplifies to $K_2^2/K_1^2 \times r_1$, since v_1 is approximately equal to e_1 and e_2/e_1 is equal to K_2/K_1, as may be shown from equation (23).

An important characteristic of rotary transformers, which limits their usefulness in larger sizes, is that the output voltages cannot be regulated by controlling the field current. This may be shown by considering equations (24) and (25). Equation (24) can be rearranged to show that the product, $n\phi$, of speed and magnetic flux is equal to $(v_1 - i_1 r_1)/K_1$. From this it can be seen that, providing the volt drop, $i_1 r_1$, is small compared with the input voltage, v_1,

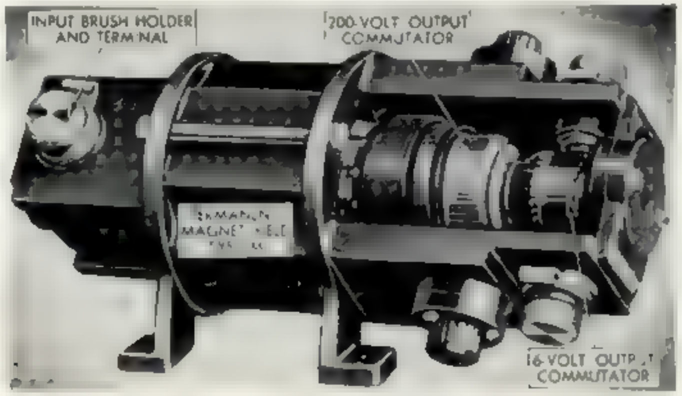


FIG. 8.5. *Small rotary transformer having two d.c. outputs for radio supplies.*

and also the v_1 is constant, the product $n\phi$ must be constant. This is a characteristic of d.c. motor operation. Knowing that the product $n\phi$ is constant we can see from an inspection of equation (25), which is $v_2 = K_2 n\phi - i_2 r_2$, that the output voltage, v_2, is unaffected by changes of flux and the consequent changes of speed. Since the equations assume normal motor and generator action it is not true to say that v_2 is unaffected by speed, since if speed changes are brought about by externally applied torque, v_2 is affected. It is unaffected only by the combined effects of a change of flux and the consequent change of speed. Since the output voltages are unaffected by changes of flux, the field current is an ideal quantity with which to regulate the machine speed and hence the frequencies of any a.c. outputs.

The only practicable way of regulating the output voltages of a rotary transformer is to control the input voltage, v_1. From equations (30) and (31) it can be seen that a change of v_1 causes a nearly proportional change of both

output voltages, since the second and third terms and the volt-drop $K_2/K_1 \times i_1 r_1$ are small compared with $K_2/K_1 \times v_1$. Independent regulation of the output voltages cannot be achieved by this method. The method has the further disadvantage, if there are a.c. outputs, that it affects the speed of the machine and hence the frequencies of the outputs. This may be seen from an inspection of equation (29). Control of the input voltage necessitates having a variable resistor in the input line and is practicable only for machines of less than about 250 watts output. With larger machines the power wasted in the regulator resistance and the size and weight of the regulator are prohibitive.

A small rotary transformer is shown in Fig. 8.5. The high- and low-

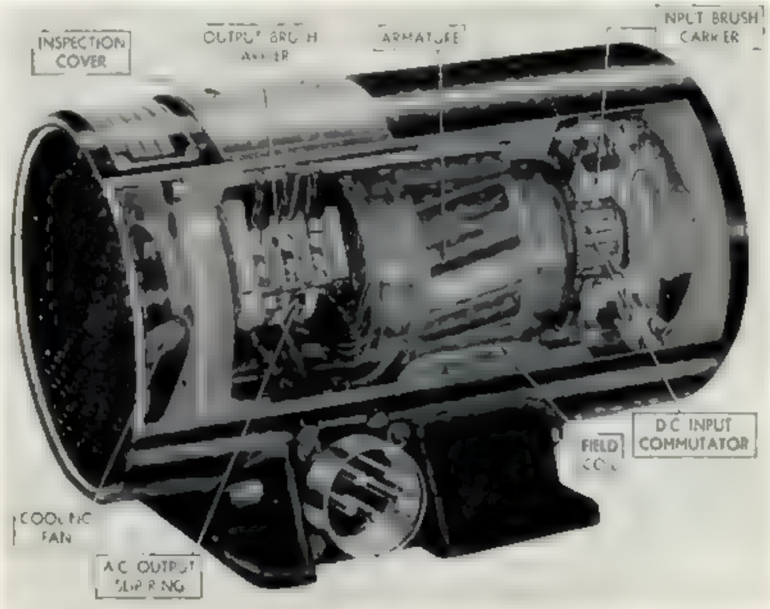


FIG. 8.6. *Modern rotary transformer having a three-phase output.*

voltage output commutators are visible and these, together with the input commutator at the opposite end of the machine, are connected to separate windings on the common armature core. Since the outputs are both d.c., speed is unimportant and permanent magnets are used to provide the field. This is not common practice for rotary transformers, and with larger machines weight is generally saved by using electro-magnets.

A larger rotary transformer having a 400-c/s three-phase a.c. output at 115 volts is shown in Fig. 8.6. This type is extensively used in modern aircraft to supply current to flying instruments and auto-pilots. It is continuously

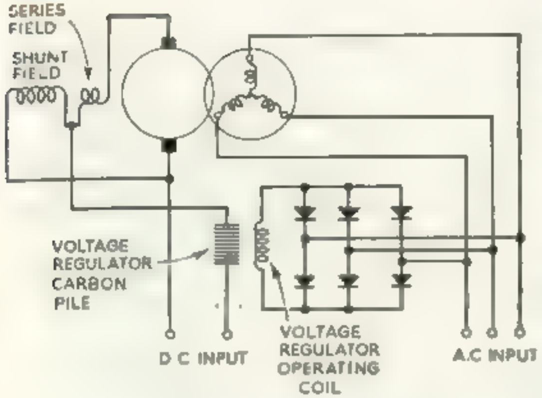


FIG. 8.7. *Simplified connexions for voltage and frequency regulation of the rotary transformer shown in Fig.* 8.6.

rated at nearly 200 volt-amperes at 0·8 power-factor and weighs 6 lb. It is self-cooled by an overhung fan (at the slip-ring end of the shaft) which provides adequate air flow up to 35,000 feet. Operating speed is 12,000 r.p.m. and full-load efficiency is a little higher than 53 per cent. The circuit of this machine and its regulator is shown in Fig. 8.7. Since the d.c. side is essentially a shunt motor, the armature-input voltage, v_1, is also the shunt-field voltage, and changes of v_1 have relatively little effect on speed. This is because speed is approximately proportional to armature voltage and inversely proportional to flux. Thus the carbon-pile resistor, which is in the d.c. input line, regulates the output voltage but has little effect on output frequency. The effect on speed of changes in load are offset to some extent by the small series winding which functions as in a compound d.c. motor.

ROTARY TRANSFORMER WITH AUXILIARY ARMATURE

An auxiliary armature is a means of overcoming the difficulties of voltage regulation of large rotary transformers, and when fitted to a rotary transformer sometimes gives a lighter machine than a motor-generator. A circuit diagram of such a machine is shown in Fig. 8.8. The auxiliary armature has a field system independent from that of the main armature which carries electrically separate input and output windings. If, as in the diagram, the auxiliary armature is connected in series with the input winding, it may

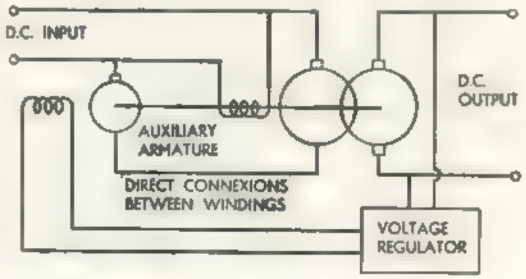


FIG. 8.8. *Method of connecting a rotary transformer having an auxiliary armature for voltage control.*

function as a motor and its field must be weakened if for any reason the output voltage falls. In this way the machine speed will be increased and the output voltage maintained constant. In the previous section (*see Rotary Transformers*) it was emphasized that only those speed changes resulting from flux changes have no effect on the output voltage; this is an example of a speed change resulting from an externally applied torque since the auxiliary armature is really a separate machine from the rotary transformer.

Several variations of the circuit are possible. The auxiliary armature may be in series with either input or output windings if the output is d.c.; if the output is a.c., then only the former arrangement is practicable. If the output of the machine is a.c. then the frequency can be regulated by controlling the auxiliary field, and the voltage by controlling the main field.

Servicing. The principles of servicing a.c. and d.c. generators discussed in Chapter 5, are also applicable to rotary converting machines, which are essentially combinations of a.c. and d.c. machines. Convertors with built-in voltage and frequency regulators are usually subjected to regulation checks after overhaul to ensure that output voltages and frequencies are within limits at extremes of load and input voltage. A check on the direction of rotation of the shaft for a specified input polarity and a phase-sequence check of polyphase outputs are usual. Inspections are usually scheduled after 100 to 250 hours of operation, and overhauls after 500 to 1,000 hours.

STATIC CONVERTING EQUIPMENT

THE principal items discussed under this heading are transformers and rectifiers which, unlike some of the rotating convertors, are each capable of only one type of converting function. Combinations of these and other static components are used to extend the range of functions, but with the exception of the simple transformer-rectifier unit, these are not yet in general use. Because static equipment requires little servicing and also because good efficiencies are attainable at small ratings, it is not uncommon to find items of utilization equipment with their individual transformers or rectifiers.

TRANSFORMERS

Transformers are designed for the standard aircraft frequencies and also for frequency ranges of variable-frequency systems. Their weight is determined partly by operating frequency, being greatest at low frequencies. High frequencies cause high iron losses and significant losses arising from eddy-currents in the conductors. As a compromise between weight and high losses, the standard 1,600 c/s supply appears to be near the optimum, but 400 c/s is not unreasonably low.

To minimize iron losses, laminations are somewhat thinner than usual

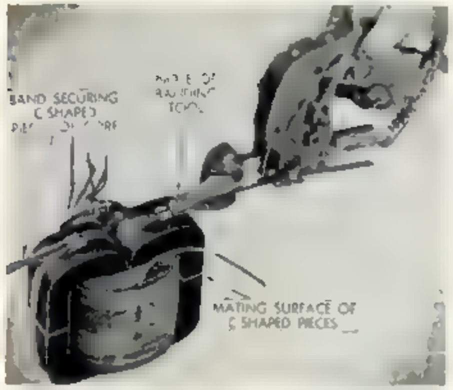


FIG. 8.9. *Single-phase transformer using strip-wound "C" cores.*

and are essentially of a material having a fairly high resistivity. Silicon iron of 0·005 to 0·012 in. thickness is a common choice for frequencies around 400 c/s, and silicon-iron or nickel-iron alloy of 0·004 in. thickness for 1,600 c/s. These materials are operated at a peak flux density of 14,000 to 16,000 lines per square cm. at 400 c/s, and 10,000 to 12,000 lines per sq. cm. at 1,600 c/s. A type of core which is gaining popularity in Great Britain is the strip-wound core. These cores are wound, rather like a clock spring, with grain-orientated silicon iron. A single-phase transformer may use one or two strip-wound cores, each of which is cut into two C-shaped parts, to allow the pre-wound coils to be fitted. Before cutting, the core is bonded to prevent separation of the layers, The cut faces are often ground to give a very small effective gap which helps to minimize the excitation current.

Fig. 8.9 shows a single-phase transformer using two "C" cores, and a method of banding the C-shaped pieces together. The outstanding merit of "C" cores is that they permit the use of grain-orientated material in such a way that the direction of orientation, which is also the direction of greatest permeability, always coincides with the transformer flux paths. For three-phase transformers the "E" core (Fig. 8.10), is the equivalent of the "C" core.

For weight economy fairly high current densities are used in aircraft transformers, sometimes as high as 15 amp. per sq. mm. With such densities forced-air cooling is essential. Much lower densities are often used, either

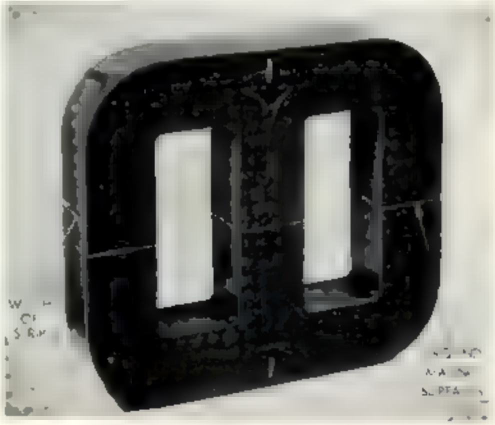


FIG. 8.10. *Strip-wound core for a three-phase transformer.*

because it is desired to avoid the need for forced-air cooling, or because it is necessary to minimize the winding resistance in order to obtain low voltage regulation. Voltage regulation may be defined as the change of terminal voltage between no-load and full-load, divided by the no-load voltage. In small transformers, where the number of turns per volt is high, winding resistances tend to be high and are frequently the cause of high voltage regulation.

Windings are formed before assembly, and after assembly the entire transformer is varnished, or else impregnated and baked. Impregnating

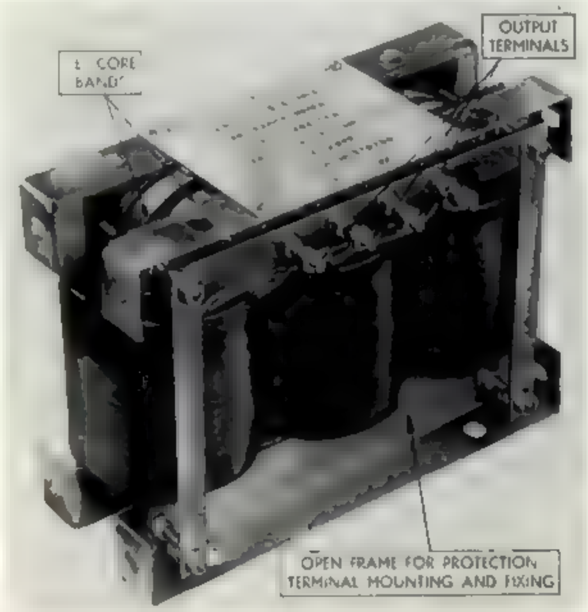


FIG. 8.11. *A completed three-phase 400 c/s, 5 kVA transformer using the "E" core shown in Fig.* 8.10.

materials serve both as a protection against moisture and to conduct heat from the coils. The choice of materials for insulation and impregnation depends on the operating temperature. Where this is high, as in transformers designed for high current densities, glass and asbestos are used. with organic impregnation these materials are satisfactory up to about 140 deg. C. and with silicone impregnation up to about 200 deg. C.

A completed 400 c/s three-phase transformer using the "E" core shown in Fig. 8.10 and rated at 5 kVA, is shown in Fig. 8.11. Its weight is 18 lb.

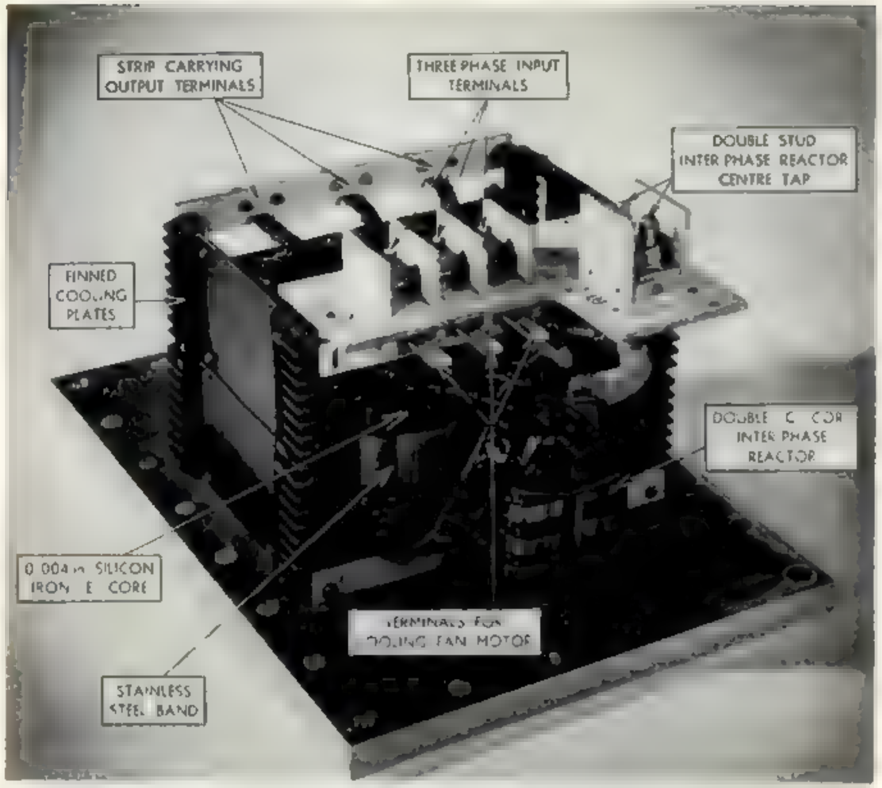


FIG. 8.12. *Ferranti air-blast-cooled three-phase transformer rated at 15 kVA; it is designed for operation over a frequency range of 320 to 500 c/s. The transformer is shown mounted on a relatively rigid plate for vibration testing, the vibration input being applied to this plate. Details of vibration-test procedure are given on page 23.*

Specific weights for 400-c/s transformers of more than about 1-kVA output usually lie in the range 2 to 5 lb. per kVA and some forced cooling is generally necessary. Fig. 8.12 shows a transformer designed for the transformer-rectifier unit shown in Fig. 11.32. It is fitted with a strip-wound core and has a double three-phase secondary winding the neutral points of which are interconnected by a centre-tapped inter-phase reactor. It is capable of continuous operation at 15 kVA with cooling air at 85 deg. C. and at an altitude of 10,000 feet. The flow of cooling air required at this loading and altitude is 90 cu. ft. per minute and the hot-spot temperatures do not exceed 200 deg. C. The unit weighs about 35 lb., which is a low value if account is taken of special features such as the interphase transformer, and additional winding for the cooling-fan motor.

THREE-PHASE TRANSFORMER CONNEXIONS

Star-Delta Windings. The choice of windings for the primary and secondary of a three-phase transformer may be influenced by several considerations. The most apparent, although not always the most significant, differences between star and delta windings are indicated as follows: *Star-winding voltage,* $v\sqrt{3}$; current, i. *Delta-winding voltage,* v; current, $i\sqrt{3}$. It follows that a delta winding requires more turns of wire (of thinner gauge) than the corresponding star winding, and it is sometimes easier to manufacture one than the other.

Neutral Connexions. Only a star winding can have a neutral connexion capable of supplying power. It is always possible, however, to provide a point at neutral potential by connecting a high-impedance star network between the lines but this is generally useful only as a voltage-reference point. If single-phase loads have to be powered from a three-phase supply it is not always practicable to keep them balanced, and a neutral power connexion is then essential.

The interconnexion of neutral points of two star windings is sometimes undesirable because this provides an external path for the flow of certain harmonic currents. These can give rise to interference with communication equipment. The provision of a low-impedance path for these currents is sometimes advantageous because it results in an improvement in the transformer voltage waveforms, but in such cases it is preferable to provide a path within the windings. The simplest method is to connect one of the two windings in delta. For these reasons many aircraft transformers have one star and one delta winding, the former being the output winding if the transformer feeds an unbalanced load.

Operation Under Fault Conditions. Consideration is sometimes given to the operation of transformers in the event of one phase failing. Short-circuited windings will generally cause overheating and necessitate de-energizing the transformer, but some connexions permit continued operation in the event of an open-circuited winding. If a double-star transformer has one winding open-circuited, two of the three output windings become energized in phase unless both the neutral connexions are in use, in which case a two-phase supply is maintained.

An open circuit in a delta winding reduces the power-handling capacity to $1/\sqrt{3}$ times normal but otherwise permits normal three-phase operation. A delta-delta transformer is therefore relatively invulnerable to open-circuit faults. Faults in star-delta and delta-star transformers depend on the winding in which the fault develops, and the effects may be deduced from the foregoing notes.

Vee-vee Transformers. In some control circuits, such as the reactive load-sharing circuit described in Chapter 11, three-phase transformers handling

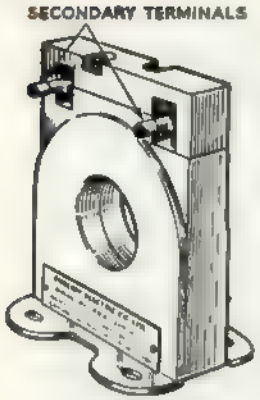


FIG. 8.13. *Current transformer for use in protective circuits of a.c. systems.*

low power are of the vee-vee type. These may be likened to delta-delta transformers with two corresponding windings removed or open circuited.

Phase Relationships. Star-delta and delta-star transformers have a phase relationship between primary and secondary quantities which must be taken into account in networks using several transformers, and which may sometimes be used to advantage. Since the induced voltages in the corresponding primary and secondary windings are in phase, it follows that the primary and secondary line voltages are displaced by 30 deg. This effect has been used in the transductor-controlled voltage-boosting circuit described in Chapter 11 (*see Regulation of Multiple Outlets*).

INSTRUMENTATION AND CONTROL TRANSFORMERS

Potential and current transformers are used extensively in a.c. systems as components of regulating and protective systems and occasionally in conjunction with indicating instruments. Extremely high accuracy is not generally required but, as with all aircraft components, considerable attention is given to detail design to ensure correct installation and subsequent trouble-free operation. Fig. 8.13 shows a current transformer of simple external form. The primary winding is constituted by a cable of the power system which is passed through the centre, and the secondary winding of 125 turns is brought out to the terminals. To avoid incorrect installation, the direction of the cable run forming the primary is indicated and the secondary terminals are marked and are of different sizes. This transformer uses a circular strip-wound core of grain-orientated silicon iron. Cutting of the cores is avoided in order to minimize the magnetizing current, and the choice of core material ensures low losses, both of which would detract from the accuracy of the transformation ratio. The transformer is encapsulated in synthetic resin which affords protection for the secondary winding and seals the unit against humidity.

RECTIFIERS

Predominant in aircraft power rectification is the selenium metal rectifier, and almost invariably it is used for full-wave rectification of a three-phase supply. Before the development of selenium rectifiers, the generation of a.c. power for rectification and use as d.c., was not very attractive because of the

weight and volume of copper-oxide rectifiers. The superior performance of selenium rectifiers changed this situation and many modern aircraft have rectified a.c. power systems. The selenium rectifier is, however, already seriously challenged by the silicon rectifier, which offers even better performance.

Germanium rectifiers lie, in order of development, between selenium and silicon, but have not been adopted in aircraft power systems mainly because they are restricted to an operating temperature of about 90 deg. C. Owing to their small thermal capacity, even short-duration overloads can cause excessive temperature rises, and to be safe, the normal operating temperature must be substantially less than 90 deg. C. This limitation, which is made critical by the difficulty of protecting the rectifier against short-duration overloads, and the development of silicon rectifiers, has deprived the germanium rectifier of a place in aircraft power systems.

SELENIUM RECTIFIERS

The selenium rectifier used in aircraft is formed on a metal sheet which serves both as a base for the rectifying junction and as a surface for heat dissipation. The rectifying junction covers one side of the sheet with the exception of a narrow strip at the edges and a small area around the fixing holes. Fig. 8.14 illustrates the make-up of a selenium rectifier. The base is aluminium, in preference to steel, which is used in industrial equipment. Selenium, which can exist in several allotropic forms, is deposited on one surface and converted to the beta form by heat treatment. A layer of insulating varnish is then sprayed around the fixing holes and, over this and the selenium, a thin layer of a low-melting-point alloy. Rectification occurs at the junction of the low-melting-point alloy, which is called the counter electrode, and the selenium.

The thickness of the base is determined by mechanical considerations. Difficulties have been experienced with the base plate being set into vibration by the flow of cooling air as well as by vibration transmitted through the mountings. Contact with the two elements of the rectifying junction, or interface, is made through the base on one side and the counter electrode

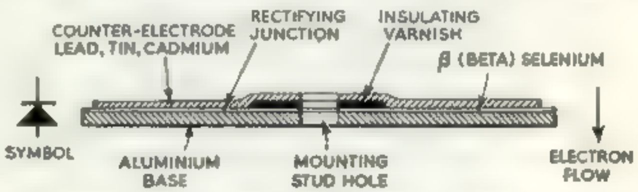


FIG. 8.14. *Illustrating the cross-section of a selenium rectifier plate. The layer thicknesses are exaggerated.*

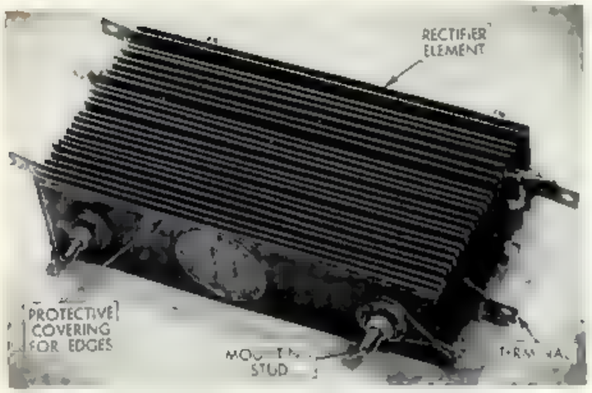


Fig. 8.15. *A stack of aluminium rectifier elements, part of the Bristol "Britannia" 112-volt, 15 kW rectifier.*

on the other. Mechanical pressure on the rectifying junction tends to lower the reverse resistance and is prevented in the region of the mounting studs by the layer of varnish. A number of rectifiers, assembled as a stack, is shown in Fig. 8.15. The plates are 3 × 12 in. and three such stacks, connected to form a three-phase bridge circuit, weigh about 24 lb. and have a d.c. output of 15·1 kW. At this rating forced-air cooling is necessary.

SILICON RECTIFIERS

Unlike selenium, silicon rectifiers do not have large rectifying interfaces and the two types differ radically in appearance and size. It is, however, often necessary to fit silicon rectifiers to large metal plates in order to dissipate heat from the junction. Fig. 8.16 shows a type of silicon rectifier. The silicon is a wafer, cut from a single crystal, with a fused-aluminium-alloy contact on one face and a soldered contact on the other. The rectifying action takes place at the aluminium-silicon junction. To avoid contamination, which occurs readily and impairs the performance, the junction is hermetically sealed. The copper base serves as one terminal and also provides a path for heat flow from the junction. Fig. 8.17 shows a silicon rectifier having an over-all length, including the lead, of about 6 in. and a body diameter of less than ½ in. The fixing stud is threaded ¼-in. B.S.F.; 36 of these rectifiers in a double three-phase half-wave circuit, mounted on copper plates and cooled with forced air, can deliver nearly 12 kW at 112 volts, or 3 kW at 28 volts. Each arm of the rectifier circuit consists of six rectifiers in parallel.

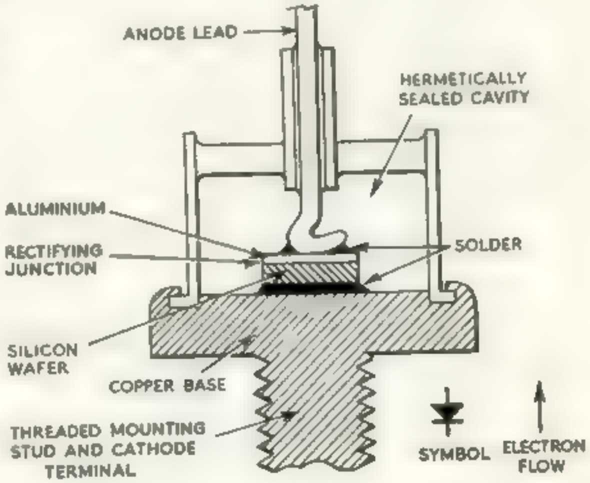
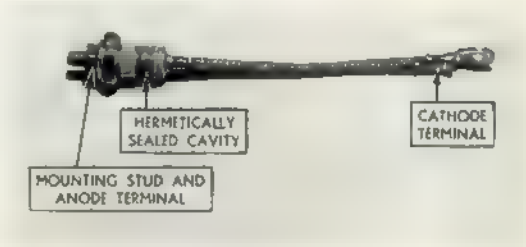


Fig. 8.16. *Cross-section of a hermetically sealed silicon rectifier.*

Fig. 8.17. *Silicon rectifier rated to deliver 60 amperes at a peak inverse voltage of 200 volts.*



An assembly of six large silicon rectifiers in a three-phase full-wave bridge circuit is shown in Fig. 8.18. The unit is capable of an output of 14 kW at 28 volts when air-blast cooled. The rectifiers are in good thermal contact with substantial heat sinks which themselves are fitted with small "radiator blocks" to present a large heat-dissipating surface to the air stream.

CURRENT RATING AND OVERLOAD

Current rating is limited by the temperature of the rectifying junction and is therefore directly dependent on the method of cooling. A junction

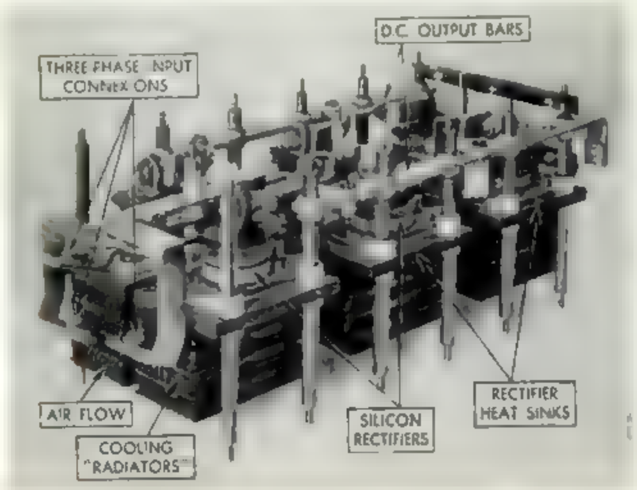
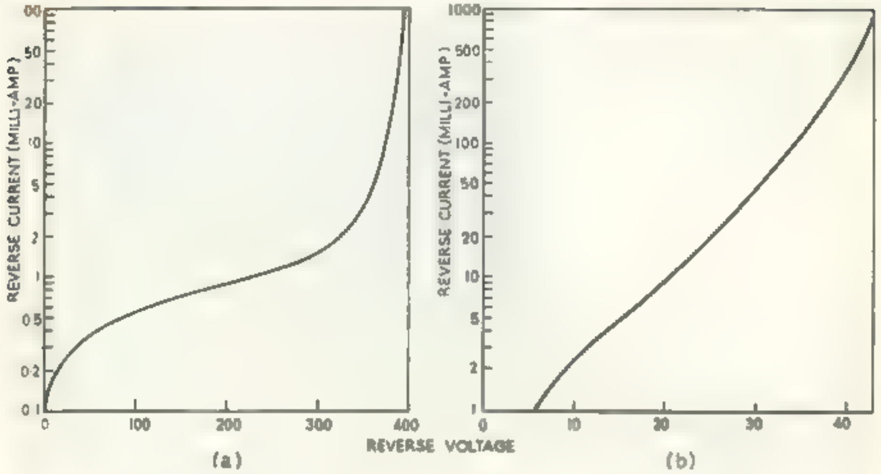


Fig. 8.18. *An assembly of silicon rectifiers capable of an output of 500 amperes at 28 volts when blast-cooled.*



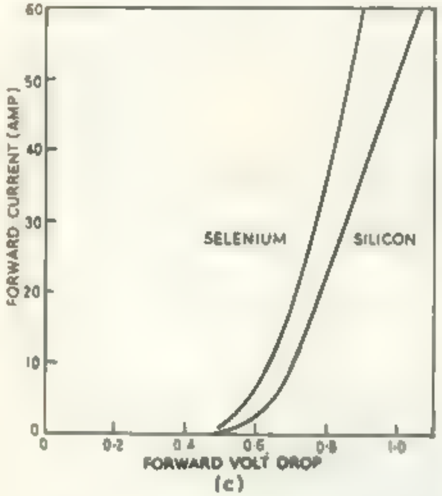


FIG. 8.19. *Reverse voltage / current characteristics for typical power rectifiers:* (a) *silicon rectifier,* (b) *selenium rectifier.* (c) *Forward current/volt drop characteristics for typical power rectifiers.*

temperature of only 80 to 85 deg. C. is permissible for selenium, although immediate breakdown does not occur until the melting point of the counter electrode is reached—about 160 deg. C. Operation at intermediate temperatures causes rapid deterioration of performance, known as ageing. Silicon rectifiers fail at about 200 deg. C. and are rated to operate in the range 120 to 150 deg. C. Compared with electrical machines, selenium rectifiers have little thermal capacity, and a relatively fast temperature rise is caused by overloading. Silicon rectifiers, however, have practically no thermal capacity, owing to the small size of the rectifying junction, and overloads of only a few milli-seconds duration, say the operating time of a fuse at 10 times normal current, can cause dangerous temperature rises.

The only practical safeguard against exceeding the critical junction temperature of 200 deg. C. is to operate the rectifier at a much lower temperature. Thus, the differences between the operating and failing tempera-

tures of the two types are necessary for different reasons: to avoid ageing of the selenium rectifier and to provide a safeguard for the silicon rectifier. With forced-air cooling selenium rectifiers are operated at current densities up to 0·8 amp. per sq. inch of rectifying junction area, and silicon rectifiers are operated at densities over 1,000 times greater.

REVERSE VOLTAGE AND BREAKDOWN

Voltage ratings are determined by the ability of a rectifier to withstand reverse voltage without passing excessive reverse or leakage current, or breaking down. Present selenium rectifiers are rated at more than 40 volts whereas copper-oxide rectifiers are rated at only 5 to 10 volts. This means that, except in low-voltage applications where the full reverse voltage rating of the selenium rectifier is unnecessary, one selenium rectifier can replace between 4 and 8 copper-oxide rectifiers. This high figure of 40 volts is the result of development over a number of years and is more than twice the value applicable to early selenium rectifiers. Silicon rectifiers can be obtained with reverse voltage ratings up to about 400 volts.

Unlike the other types, the manufacturing processes of silicon rectifiers yield specimens with widely differing reverse voltage/current characteristics and these are selected and marketed as rectifiers with different ratings, from about 40 to 400 volts. Voltage overloads can destroy silicon rectifiers by causing a large increase in reverse current, thus overheating the junction. This may be verified by reference to Fig. 8.19 (*a*) which shows a marked change in the slope of the reverse-voltage/current characteristic at about 350 volts. Selenium rectifiers are not quite so critical owing to their greater thermal capacity and more gradual increase of reverse current with voltage. It has been observed that a local breakdown of the selenium rectifier junction, caused by a momentary application of excess voltage, is self-healing owing to the melting and reformation of the selenium in another allotropic form, gamma, which is an insulator.

LOSSES

Losses occur and heat is generated by the flow of both forward and reverse or leakage currents. Silicon rectifier elements have a slightly higher forward volt drop than selenium elements but, except in low-voltage circuits where a single selenium element is adequate, this extra drop is more than offset by the fact that less rectifier elements are used in series, The forward volt drop at full output is between 1·0 and 1·5 for silicon and 0·8 and 1·1 for selenium. From the characteristics in Fig. 8.19, the forward losses of those particular rectifiers at 60 amp. are $60\times0{\cdot}9=54$ watts, and $60\times1{\cdot}06=63{\cdot}6$ watts for selenium and silicon respectively. Reverse losses, which may be significant in copper-oxide rectifiers, are small in selenium rectifiers and

almost insignificant in silicon rectifiers. Again from Fig. 8.19 (*a*) and (*b*), at 30 volts the reverse losses of the selenium rectifier are $30 \times 0{\cdot}046 = 1{\cdot}38$ watts, and of the silicon rectifier at 300 volts, $300 \times 0{\cdot}0015 = 0{\cdot}45$ watts. Values depend on the size of the rectifiers and also vary considerably between rectifiers of different manufacture. Germanium rectifiers have much lower forward losses than either silicon or selenium and can withstand reverse voltages of 150 to 200 volts. For rectifying at that level of voltage they are therefore more efficient than the other types, and if operation below their junction temperature limit of 90 deg. C. could be assured, they would be well suited for providing the standard 112-volt supplies.

CONTROLLED SILICON RECTIFIER

This is a development of the silicon rectifier and has some of the characteristics of a thyratron valve. It is a three-terminal device, two terminals corresponding to those of an ordinary rectifier and the third to the thyratron grid. When reverse voltage is applied the device behaves as a normal rectifier, but when forward voltage is applied current flow is practically zero until a critical forward "break-over" voltage is reached. The value of break-over voltage can be changed by passing very small currents between the third terminal, the gate, and the cathode. Once conduction has been started it can be stopped only by reducing the applied voltage to a very low value. If used in a rectifier circuit, the mean value of rectified voltage can be controlled by adjusting the phasing of the gate signal with respect the applied voltage, as in grid-controlled thyratron and mercury-arc rectifiers. The device has only recently become available and has not yet been used in aircraft power rectifiers.

Forward and Reverse Resistances. It is often convenient to consider resistance/current or resistance/voltage characteristics instead of the voltage/current characteristics shown in Fig. 8.19. These may be determined from Fig. 8.19, for the particular rectifiers represented, since the resistance at the conditions represented by any point on the curves is equal to the voltage ordinate divided by the current abscissa. For example, at 60 amp., forward resistances are $0{\cdot}9/60 = 0{\cdot}015$ ohm and $1{\cdot}06/60 = 0{\cdot}0178$ ohm for the selenium and silicon rectifiers respectively. Similarly, at a reverse voltage of 30 volts the reverse resistance of the selenium rectifier is $30/0{\cdot}046 = 652$ ohms, and at 300 volts that of the silicon rectifier is $300/0{\cdot}0015 = 200{,}000$ ohms.

For all types, resistance is high at very low forward and reverse currents. Reverse resistance remains high but decreases as reverse current is increased. Forward resistance falls to a low value even at quite small forward currents and decreases further as current is increased. Thus it is common practice, when considering the operation of rectifier circuits, to assume that rectifiers have zero forward resistance and infinite reverse resistance.

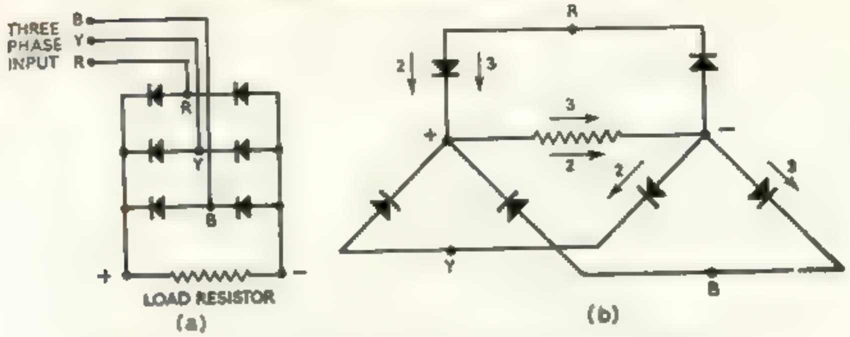


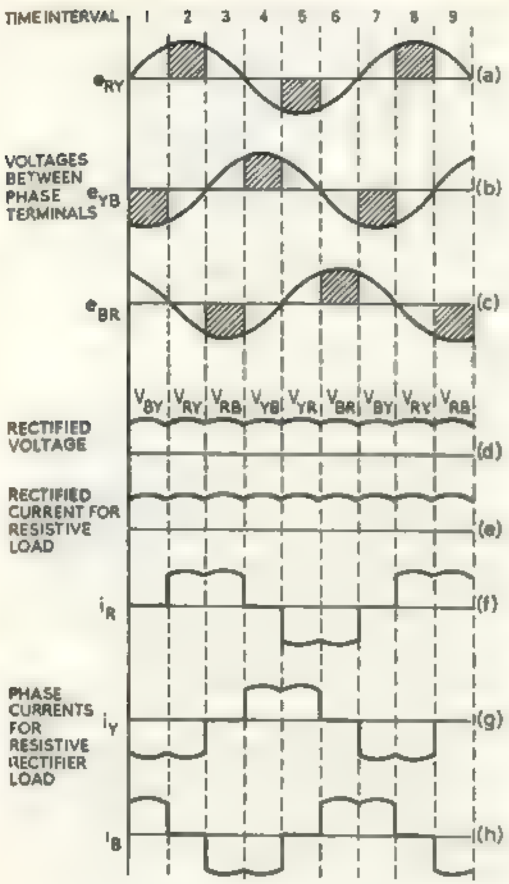
FIG. 8.20. *Circuit diagrams of three-phase bridge rectifiers.*

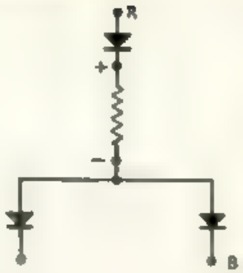
THREE-PHASE BRIDGE RECTIFIER CIRCUIT

This circuit is the one most commonly used for power rectification in aircraft. It has several useful features among which is that of suitability for direct connexion to a three-phase supply without the use of a transformer. Its output-voltage waveform is relatively smooth and the ripple frequency is high and easily filtered. the circuit of the rectifier is often drawn as in Fig. 8.20 (*a*) but the operation will be described by reference to an alternative layout shown in Fig. 8.20 (*b*).

Operation. To study the operation it is convenient to consider all the possible paths along which current might flow between the three phase terminals *R*, *Y* and *B* in Fig. 8.20 (*b*). Paths which traverse any two arms of the same star of rectifiers, such as the paths *R*,+, *Y* and *R*,+, *B*, are closed paths because they contain two rectifiers connected in opposite senses. Also closed, are paths which include corresponding arms of each star, such as *R*, +,−, *R* and *Y*,+,−,*Y*, because the only potential difference existing in these circuits is that across the load resistor, and this is opposed by the reverse resistance of the two rectifiers. The remaining paths between any two of the terminals, *R Y* and *B*, of which there are only six, are those which traverse one arm of each star and where the arms do not occupy corresponding positions. Examples of these paths are *R*,+,−,*B* and *R*,+,−,*Y*. It is approximately true, for reasons which are discussed later (see *Change of Conducting Path*) that at any instant in time, current is confined to one of these six paths. The conducting path is that which lies between the pair of three-phase terminals having the greatest difference in potential.

Fig. 8.21 (*a*), (*b*) and (*c*) show the waveforms of voltages existing between each of the pairs of phase terminals. For example, e_{RY} is the potential of terminal *R* with respect to terminal *Y*. The waveform time scales are divided into time intervals of one-sixth of a period, because the greatest potential difference, and therefore conduction, exists between each of the pairs in





(Left) FIG. 8.21. *Waveforms for the three-phase bridge rectifier.* (Above) FIG. 8.22 *The part of the circuit which is operative during intervals 2 and 3.*

succession for these periods. Consider, as an example, time interval 2 when the greatest potential difference exists between terminals R and Y, and current flows along the path $R,+,-,Y$ as indicated by the arrows marked 2 in Fig. 8.20 (*b*). Conduction is also indicated on the voltage waveforms by shading under the curves.

VOLTAGE AND CURRENT WAVEFORMS

To simplify the deduction of waveforms it will be assumed that the rectifiers have zero forward resistance and infinite reverse resistance. The fairness of this assumption may be assessed by considering the rectifier characteristics previously discussed (see *Current Rating and Overload*; *Losses*). On this assumption it follows that the voltage existing across the load resistor is identical in form with the voltage at the phase terminals between which conduction is occurring. The polarity is, however, always in the same sense because there are two possible paths between each pair of phase terminals, such as $R,+,-,B$ and $R,-,+,B$ between the pair RB, and conduction follows one path or the other depending on the polarity of e_{RB}. Thus, the rectified voltage waveform is a series of sine-wave peaks, six peaks occurring in one period of the a.c. supply as shown in Fig. 8.21 (*d*).

Rectified current, provided the load is purely resistive, is identical in form with the rectified voltage, as shown in Fig. 8.21 (*e*). If the load is partly reactive the current waveform differs from the voltage waveform in a manner which may be determined by considering the voltage waveform to consist of d.c. with an a.c. component superimposed. A partly inductive load, such as might be constituted by the use of smoothing chokes, offers a high impedance to the a.c. component and allows only a small component to flow.

Assuming a resistive load, the currents flowing into the circuit from each phase terminal are as shown in Figs. 8.21 (*f*), (*g*) and (*h*). These waveforms follow directly from the preceding waveforms if current passing a terminal is considered positive when the terminal is positive. As an example, in time interval 1 the greatest potential difference is e_{YB}, and Y is negative with respect to B, thus i_Y is shown as negative and i_B as positive. The shape of these waveforms is of interest because they are of the current delivered to the rectifier from the a.c. supply, which is either a transformer or an a.c. generator. The harmonic content of this current is high, and instances have occurred where this has caused unexpected heating in a.c. generators.

Rectifier current waveforms consist only of the positive or negative parts of the phase-current waveforms, since there are two possible paths between each pair of phase terminals, and the rectifiers ensure that each path accepts current of one sense only.

Change of Conducting Path. On p. 147 it was stated that conduction is confined at any instant to a particular conducting path. This is approximately true and may be understood by considering time intervals 2 and 3, Fig. 8.21. At the end of period 2, conduction is changing from path RY (Fig. 8.20) to path RB and $e_{RY}=e_{RB}$, since $e_{RB}=-e_{BR}$. At a very short time, t, after the end of period 2, e_{RY} is less than e_{RB} by a small potential difference δe. But from Fig. 8.22, which shows that part of the circuit which is operative during these two intervals 2 and 3, e_{R-} is a potential difference common to both paths, RY and RB. Therefore e_{-Y} is less than e_{-B} by δe.

This in itself tends to change the current flow from path RY to RB, but a further fact to be taken into account is that rectifier forward resistance depends on the forward voltage, decreasing as the voltage is increased. Hence R_{-Y} the resistance of the rectifier between the points $-$ and Y, is greater than R_{-B} by δR, and

$$i_{RY}=i_{-Y}=\frac{e_{-B}-\delta e}{R_{-B}+\delta R}, \text{ when } i_{RB}=\frac{e_{-B}}{R_{-B}}.$$

Thus the reduced voltage and increased resistance across path $-$ to Y, work together to reduce i_{RY} while i_{RB} increases and the change-over of current is more rapid than would be the case if the rectifiers were replaced by resistors. (*Note:* e_{R-} signifies the p.d. between point R, Fig. 8.20*b*, with respect to point $-$, i.e., the negative terminal.)

RELATIONSHIPS BETWEEN ALTERNATING AND DIRECT-CURRENT QUANTITIES

From inspection of the waveforms of Fig. 8.21, and with the aid of integral calculus, the following current and voltage relationships can be obtained. The rectified voltage has a mean value equal to 0·955 times the peak value of the input alternating voltage applied to the phase terminals, e_{RY} and so on. It is interesting to notice that the d.c. output voltage is thus considerably greater than the r.m.s. value of the input voltage. The ripple on the output voltage is at six times the supply frequency (2,400 c/s with a 400 c/s supply, for example), and sometimes gives rise to interference with communication equipment. Its theoretical amplitude is (1−sin 60 deg.)/2 =0·067, or 6·7 per cent of the amplitude of the input voltage. In practice, however, differences in rectifier characteristics usually give rise to an irregular ripple waveform differing considerably from the simple one shown in Fig. 8.21 (*d*).

The mean value of rectified current is 0·955 times the peak value of the alternating current, i_R and so on. Unlike the alternating voltage, however, the alternating current is of unusual waveform having an r.m.s. value equal to 0·781 of its peak value, instead of 0·707 if it were sinusoidal. Thus, the r.m.s. value of alternating current is 0·781/0·955=0·82 times the direct current. This is a useful relationship because it is often necessary to know the r.m.s. current input to the rectifier for a particular output.

To select rectifiers for the bridge, the current in each individual rectifier must be known. The waveform of this current is either the positive or the negative part of the full input-current waveform, and its r.m.s. value is 0·575 times the direct current. This is more than half the r.m.s. value of the input current and is the value for which the individual rectifiers should be rated. It is not a simple matter to calculate the heat dissipation arising from this forward current because the forward resistance is a function of the current, decreasing as the current increases. In practice, most manufacturers determine the ratings of their rectifiers in all the commonly used circuits and with various types of loads, usually by tests in which the heat dissipation is measured and the temperature of the rectifiers deduced. The results of such tests are generally published in a form which shows the maximum outputs obtainable from each of the circuits using various sizes and types of rectifiers.

From Fig. 8.20 (*b*) it can be seen that each of the rectifier arms is subjected in turn to a peak reverse voltage equal to the peak value of the voltage between the a.c. terminals. If this exceeds the peak reverse voltage rating of a single rectifier, then a number of rectifiers must be used in series in each arm of the bridge, One selenium rectifier per arm is adequate for rectification to the standard 28-volt supply, but four are necessary for 112 volts. Even at the higher voltage, one silicon rectifier is adequate.

The ratio between alternating and direct voltages quoted in the previous paragraph assumes that rectifiers have zero forward resistance and therefore takes no account of the voltage drops which occur across the rectifiers. These voltage drops are usually less than one volt per rectifier element, as indicated in Fig. 8.19 (*c*), but are often large enough to cause the terminal voltage of the rectifier to fall appreciably as the rectifier is loaded. This is particularly true with selenium rectifiers and, to a lesser extent, of low-voltage

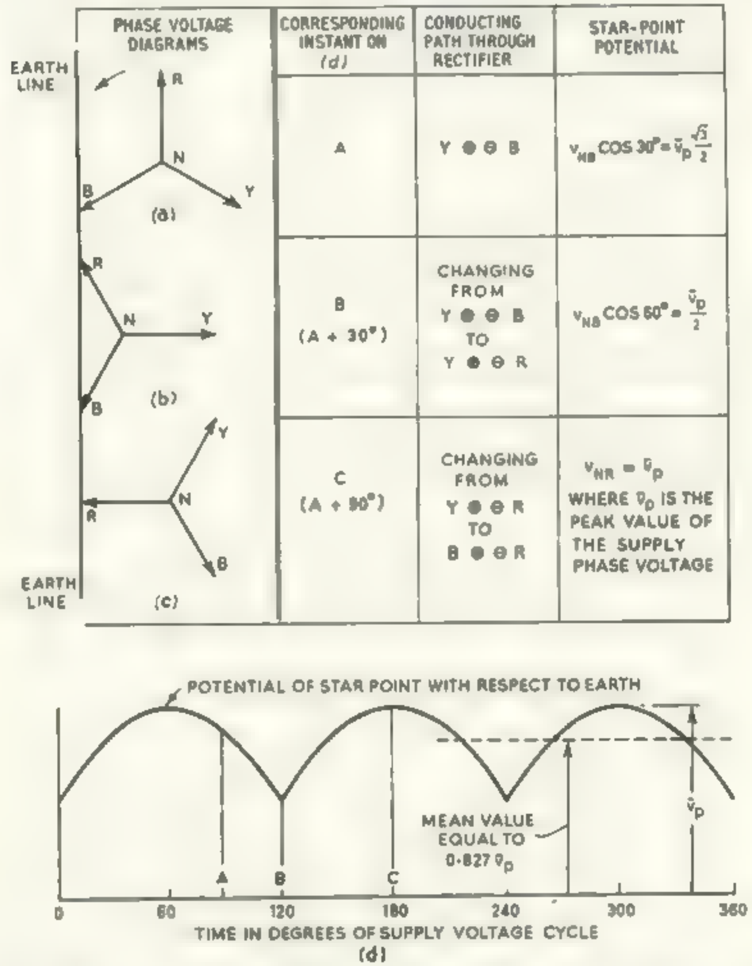


FIG. 8.23. *Diagrams* (a), (b) *and* (c) *illustrate the derivation of the waveform at* (d), *which shows the star-point potential waveform for a three-phase bridge rectifier with earthed negative output. The conducting path through the rectifier is as shown in Fig.* 8.20 (b).

silicon rectifier circuits. Since the output voltage of the rectifier can be regulated only by controlling the input voltage, the control equipment tends to be cumbersome. A regulator for a 28-volt rectifier is described in Chapter 11.

STAR-POINT POTENTIAL

Although this is of little consequence when the three-phase bridge rectifier is being considered as an a.c. to d.c. convertor it is of value in connexion with several protective circuits which are discussed in Chapter 11. For reasons discussed in the same Chapter it is usual to earth the negative output terminal of the rectifier in preference to the star point of the three-phase supply feeding the rectifier. With this connexion, and when the rectifier is delivering current, the star point assumes a mean potential which is approximately equal to half the output voltage of the rectifier. The nature of the star-point potential may be deduced in the following way.

At any instant when the rectifier is delivering power, two arms of the bridge are conducting and therefore have very low resistances. Considering the instant when the conducting path is $Y, +, -, B$, in Fig. 8.20 (*b*), the blue line is connected to earth by the arm $-B$. This is some time in period 4, Fig. 8.21. These conditions may be represented by the diagram shown in Fig. 8.23 (*a*) which is constructed for the instant half way through period 4. Fig. 8.23 (*a*) and the diagrams (*b*) and (*c*) use conventional anti-clockwise rotation of the phasors and represent instantaneous voltages by the horizontal projections of any phasor. The earth line is a reference and the supply line or lines which are temporarily connected to earth through the low forward resistances of conducting rectifiers are shown with their voltage phasors meeting the earth line. The instantaneous potential of the star point is represented by the horizontal from the star point, N, to the earth line in each diagram, and from a series of diagrams the point star potential waveform, shown in (*d*), may be deduced.

The mean value of this waveform is 0·827 of its peak value, which is the supply phase voltage. Thus for a 28-volt rectifier output the star point potential is $\frac{28}{0{\cdot}955} \times \frac{1}{\sqrt{3}} \times 0{\cdot}827 = 14$ volts. It should be noted that rectifier resistances have been neglected.

The fundamental frequency of the star-point potential waveform is only three times that of the supply and its ripple amplitude is substantially greater than that of the rectifier output. It has been proposed as a possible source of d.c. power at half the main rectifier output voltage, available without resorting to additional transformers. It has not been used as such, probably because of the inevitable interaction between the two outputs and the problem of controlling their voltages independently. When the rectifier is energized but not delivering current, all the rectifier elements have fairly high resistances

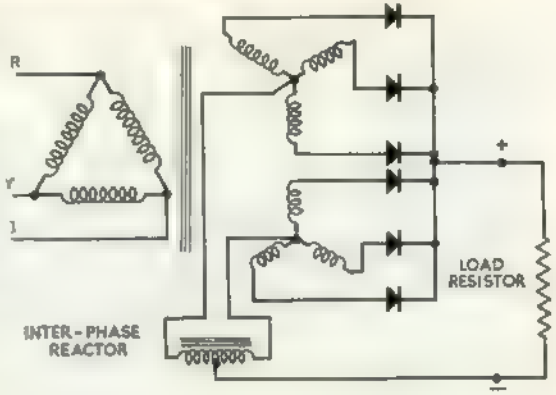


FIG. 8.24. *Double three-phase half-wave rectifier circuit.*

and under these conditions the star point is virtually isolated. This is a useful feature of the rectifier circuit which has been applied in the control arrangements of rectified a.c. systems, discussed in Chapter 11.

DOUBLE THREE-PHASE HALF-WAVE RECTIFIER

This rectifier circuit, which is shown in Fig. 8.24, has been used since silicon rectifiers became available because it has the advantage that only one rectifier arm is in series with the load during each conducting period. This halves the forward rectifier losses and voltage drop. It could not have been used advantageously with selenium rectifiers because each arm has to withstand a reverse voltage of approximately twice the rectified output voltage. This could have been met only by using at least twice as many selenium rectifier elements in series, which would have completely offset the advantage gained.

The circuit is not as simple to install as the three-phase bridge because it requires two anti-phase three-phase supplies, but if a transformer is being used there is little disadvantage in providing two secondary windings instead of one. The need for an interphase reactor is a further minor disadvantage: it is necessary to equalize the currents delivered by the pair of rectifiers, one from each star, which conduct simultaneously. This component may be seen on the transformer shown in Fig. 8.12.

The r.m.s. value of the current carried by each rectifier element is 0·294 of the total rectified output. When this is compared with 0·578 for the three-phase bridge circuit it will be appreciated that this circuit has nearly twice the current output of a three-phase bridge using the same number of identical rectifiers; this is true only when considering rectifiers with high reverse-voltage ratings for relatively low-voltage circuits. The rectified output voltage is 0·855 of the peak value of the secondary winding voltage. A detailed discussion of rectifier circuits is given in Chapter 18 of Ref. 12.

Transformer-rectifier Units. A commonly occurring combination of converting equipments is that of transformers and rectifiers, often called T.R. units. They are discussed at length in Chapter 11.

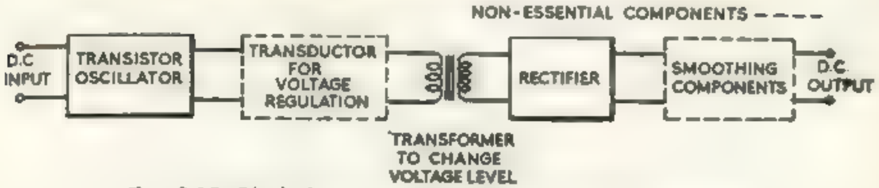


FIG. 8.25. *Block diagram of a d.c. to a.c. transistor convertor.*

STATIC D.C. TO A.C. CONVERTORS

The types of static converting equipment so far discussed, which represent nearly all the static equipment in use in aircraft, are restricted in their functions to changing the voltage level of a.c. power and converting a.c. to d.c. Fig. 8.25 shows a block diagram of a static convertor which converts d.c. to a.c. and can change direct-voltage levels. Such equipment has been technically possible since the invention of the triode valve but has not been generally practicable as an aircraft power convertor because valve oscillators are relatively large, fragile and inefficient. The principal advantage of static convertors is that they require less servicing than do rotating machines if the valves are replaced by components which are more rugged and efficient.

Vibrators. The mechanical vibrator has been available for many years as a substitute for valve oscillators and has been extensively used in some fields, such as in automobile radio-power supply units. Its life is limited by the effects of arcing at the contacts, and its reliability under aircraft conditions has never been accepted as high enough for essential supplies.

Transistor Oscillator Convertors. These units offer the same facilities as vibrator units but the function of the vibrator element is performed by a transistor oscillator. Transistors may be regarded as germanium or silicon triodes, having many of the valuable qualities of semi-conductor diodes or rectifiers, but also being capable of functioning as a vacuum-tube triode and operating as an oscillator. Transistor oscillators operate at high efficiencies if the output waveform is approximately square. This is because losses

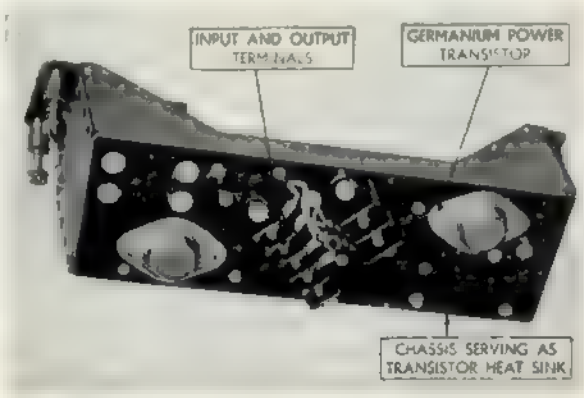


FIG. 8.26. *Transistor convertor and control unit for fluorescent lighting.*

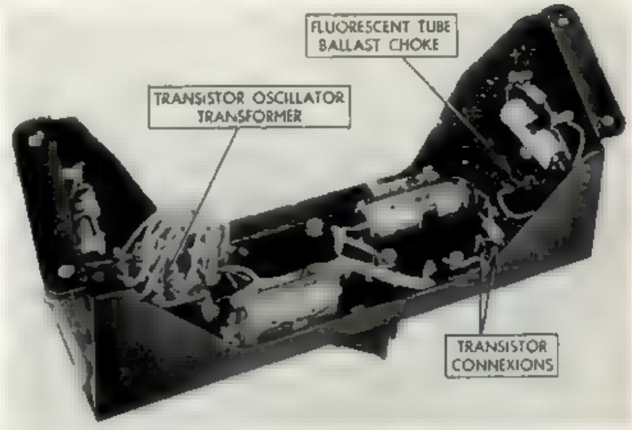


FIG. 8.27. *Internal components of the transistor convertor shown in Fig.* 8.26.

occurring in the transistors are least when they are either non-conducting or fully conducting. Square output waveform is not necessarily a disadvantage if it is to be subsequently rectified, since high rectifier efficiencies are sometimes attainable with such inputs. Where the output is to be used as a.c. power, and a better waveform is required, it is necessary to operate the transistors in a relatively inefficient way or else to use harmonic filters. Transistor oscillators can be designed for a wide range of frequency, but a practicable range for transistor convertors is 250 to 1,500 c/s. Filter chokes and transformers are heavy if designed for low frequencies, and at high frequencies losses in cores and transistors become limiting factors. Three-phase outputs are possible but, to date, have not been fully developed.

One restriction, which is imposed at present by the relatively low reverse breakdown voltage of power transistors, is that the convertors can accept only a low-voltage d.c. input. Operation at 28 volts is practicable and higher voltages are expected after further transistor development. Design information on transistor convertors is given in Ref. 10.

Simple unregulated d.c. to d.c. convertors, ruggedized for use in aircraft and hermetically sealed, are available with specific weights as low as 30 lb. per kilowatt at outputs of 150 watts. One such unit has an output of 0·2 amp. at 325 volts and weighs 3·2 lb.

Figs. 8·26 and 8·27 show a d.c. to a.c. convertor for supplying power to a fluorescent lighting tube. The unit is designed to operate at input voltages between 21 and 30 volts and to withstand the effects of transient voltages up to 64 volts. It provides two a.c. outputs, one of about 6 watts for cathode heating and another of up to 12 watts to maintain the discharge. In addition to accommodating the components of the transistor convertor the unit includes a ballast choke to control the discharge. Its total weight is 1lb.

CHAPTER 9

Power-Consuming Equipment

THE functions performed by power-consuming equipment are the "end products" or purpose for which the electrical system is installed in an aircraft. In weight it equals or exceeds that of the generating and distribution equipment together. Consuming equipment takes a variety of different forms and originates from a large number of manufacturers. Some items, such as de-icing heaters and the larger actuators are designed for particular aircraft. Because of its variety it is practicable to design or select equipment to suit the system from which it is to be powered, and the specification or choice of equipment has much to do with minimizing the total weight of electrical equipment.

LIGHTING

Lighting is a field in which electricity is unrivalled and aircraft lighting is no exception to this rule. Lights are used for a multiplicity of purposes which are, principally: (*a*) the general illumination of cabins; (*b*) the marking of the aircraft with navigation lights; (*c*) identification by lights flashing in a particular sequence; (*d*) forward illumination for landing and taxying; (*e*) the illumination of instruments and control panels; (*f*) local illumination; (*g*) indication of the condition of remotely controlled mechanisms and the operation of equipments; (*h*) passenger information signs.

General cabin illumination poses a number of problems. The even, shadow-free illumination of a small space, which is approximately cylindrical with length far exceeding its diameter, requires a distributed light source. If high-intensity lamps are used, such as high-power filament lamps, these must be concealed and the light arranged to appear indirectly by reflection, or through diffusing surfaces, in the body of the cabin. Fluorescent tubes are naturally better suited for this because light emanates from the entire tube surface instead of from a filament. The life of filament lamps for use in aircraft lies between 300 and 1,000 hours and, in a large passenger cabin, several hundred lamps may be required. This situation gives rise to a failure rate of several lamps a day and is a further point in favour of fluorescent tubes.

It is often required that the level of cabin lighting should be variable

and here fluorescent lamps are at a disadvantage because light-weight dimming equipment has not yet been developed. For obtaining various colours fluorescent lamps have an advantage, since different colours are available from tubes with different phosphors, whereas filament lamps have to be fitted with colour filters which detract from the light output.

Fluorescent tubes may be operated efficiently from the standard 400 c/s supply and satisfactorily from 112-volt d.c. and variable-frequency a.c. supplies. With a constant-frequency a.c. supply an inductor can be used to control the discharge. This gives an installation having an efficiency approximately four times that of filament lamps but a weight which is also four times greater. If the inductor is replaced by a resistor, as is necessary for operation from d.c. and variable-frequency a.c., the efficiency is reduced to about twice that of filament lamps but the installed weight is only a little greater. When both weight and efficiency are taken into account the resistor-controlled installation appears to be slightly preferable.

Illumination in aircraft cabins at high altitudes has some interesting facets arising from the fact that the aircraft is high above clouds and in an atmosphere which is relatively free from light-reflecting particles such as dust. Whereas at low levels reflected light enters the cabin through the side windows from surrounding objects, such as clouds and the ground surface, and from airborne particles, at high altitudes there is practically no light except that coming from above. Also the light intensity from above is some 25 per cent greater and other aircraft appear to be brilliantly illuminated. These conditions create a need for cabin illumination by day as well as by night and, to offset the glare from external objects, high-intensity illumination of cockpit operating surfaces.

Navigation lights invariably use filament lamps and are positioned at the wing tips, the tail and above and below the fuselage. The lamps at the extremities are subjected to fairly severe vibration, and low operating voltages are necessary in order to allow a heavy-gauge filament to be used. The standard 28-volt supply is satisfactory but it is probable that an even lower voltage would be advantageous. The port and starboard lights are coloured red and green respectively and some or all are required to flash in a specified sequence. Motor-driven cam-operated switch units and electronically controlled relay units are available for this function. Rotating beacon lights, positioned forward of the tail fin, are an additional requirement in the U.S.A. Military aircraft have used signalling lamps for identification and communication.

Illumination of the runway, forward of the aircraft, is required for landing, and of the area forward and out to the wing tips, for taxying. Landing lamps are operated only for brief periods, but as these are among the most critical in the operation of aircraft, a reserve filament is usually built into the

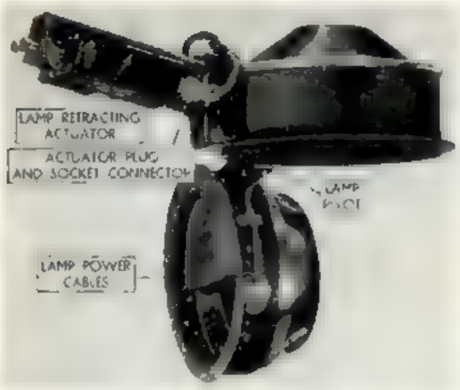


FIG. 9.1. *Electrically actuated 500-watt landing lamp in the lowered position.*

lamp bulb and is available for immediate use. Filaments are operated at slightly higher than normal temperatures in order to obtain high efficiencies, even at the expense of filament life. Ratings of up to 500 watts are commonly used, and up to 1,000 watts are under development. Two lamps are fitted on all larger aircraft. Owing to their size they are usually retracted into the underside of the main plane when not in use. A typical 500-watt lamp, lowered and retracted by an electric actuator is shown in Fig. 9.1.

Taxying lamps are of somewhat smaller rating, usually up to 250 watts, and are also fitted in pairs on larger aircraft. They are sometimes built into the leading edges of the wings, sections of which are constructed of transparent material, or alternatively incorporated in the landing lamps or fixed to the undercarriage.

Cockpit and control panel lighting has been developed to a considerable degree for night flying. The pilot requires, alternately, the best possible vision of external surroundings, most of which are in semi-darkness, and of the instruments and controls. Adaptation of the eyes from an illuminated control surface to semi-darkness is found to be easiest if the level of control surface illumination is low and if its colour is red. One method, which was extensively used in military aircraft, is to provide a low level of general cockpit illumination from red lamps, and ultra-violet light for the instruments, which are treated with a suitable phosphor. The intensity of both light sources is adjustable by the pilot. A more recent development requires the covering of all control surfaces with a special laminated plastics material, but gives results which are

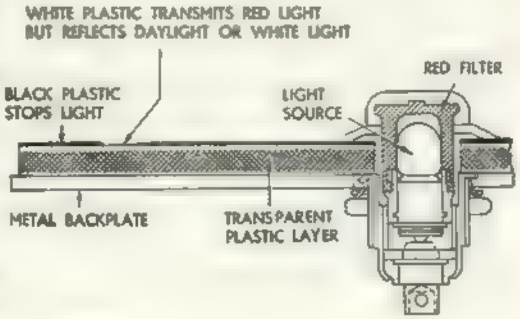
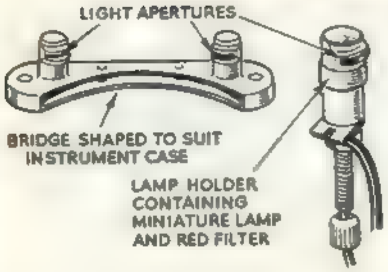
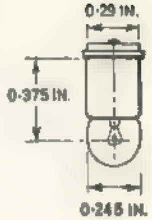


FIG. 9.2. *Illustrating the principle of the Thorn "Plasteck" panel.*



(Left) FIG. 9.3. *Instrument bridge and pillar-type lamp holders.*

(Right) FIG. 9.4. *Main dimensions of midget lamp used in Thorn "Plasteck" panel illumination.*



widely acclaimed. The material consists of a sheet of transparent plastics faced on both surfaces with layers of translucent white plastics and on one side, an additional layer of opaque black or grey plastics.

The manner in which the laminated material is used is shown in Fig. 9.2. Red light is conveyed through the transparent layer and emanates from those parts of the surface where the black plastics has been removed. Engravings for identification, indication of switch positions, etc., which penetrate the black plastics and expose the white, are illuminated in red by night but appear in white by day. Small instruments which can be recessed so that their indicating surfaces lie behind the panel surface can be illuminated by light from the transparent layer. Larger instruments cannot be illuminated directly but can be fitted with small individual lamps, or with bridge and pillar type lampholders as shown in Fig. 9.3. The light sources are low-voltage filament lamps rated at 1 watt and their size may be appreciated from Fig. 9.4. For panel illumination they are spaced between instruments and switches at a density of about 15 per sq. ft. Lamps are connected in parallel and are usually supplied from two independent circuits to ensure continuity of lighting in the event of a fault.

Local illumination is required for such things as reading, in confined spaces such as freight holds and toilets, and to illuminate steps. All these use small filament lamps, but although simple electrically need good mechanical design and manufacture to give acceptable service. Fig. 9.5

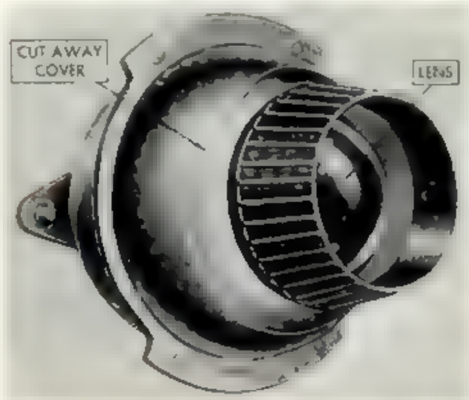


FIG. 9.5. *Passenger's reading lamp. The cut-away cover allows limited angular lens movement.*

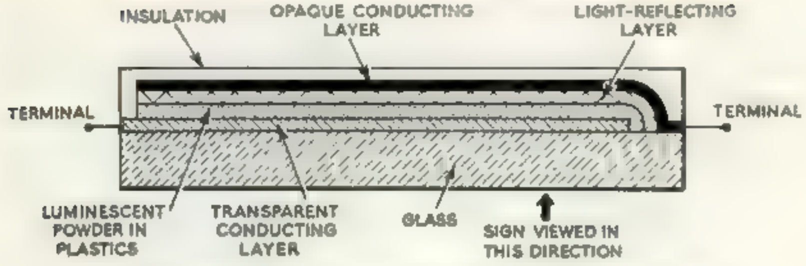


FIG. 9.6. *Illustrating the principle of an electroluminescent sign.*

shows a passenger's reading lamp which uses a lens to throw a beam of approximately 35 deg. included angle. The beam direction may be adjusted within limits by the passenger; this adjustment does not disturb the electrical wiring. Indicator lamps are used for many purposes typical of which are the indication of deviation of engine conditions from normal, the setting of trim tabs at extreme positions and the locking of aerodynamic surfaces and mechanisms; 28-volt filament lamps are in general use for these applications.

Passenger information signs, those which request passengers to "fasten safety belts" etc., have, to date, been illuminated with filament lamps, but electroluminescent panels are available. These, including their power supply transformers, weigh rather less than half as much as the conventional signs and are also thinner and consume less power. The arrangement of one type of electroluminescent sign is shown in Fig. 9.6. An a.c. voltage of about 300 volts at 400 c/s is applied to the two conducting layers and light is emitted from phosphor particles suspended in the intermediate plastics layer. One or both of the conducting layers is shaped to form the letters and symbols required for the sign and these appear as illuminated areas.

Power consumption of typical signs is only a few watts; consequently the sign can be powered from a d.c. system by using a small transistor d.c. to a.c. convertor. The future of electroluminescence for general lighting appears promising since the source is large and gives an even glare-free light. A wide range of colours can be obtained by choice of phosphors. Brightness is affected by voltage and frequency and, since some phosphors are affected more than others by frequency changes, it is possible, with a suitable phosphor blend, to change colour by changing frequency. At present, however, the efficiency of electroluminescent lamps is much less than that of fluorescent lamps, and the development of lamps for general lighting is still awaited.

HEATING

Aircraft engines, during normal operation, are a source of considerable surplus heat and where possible this is used for heating the cabin and those

parts of the aircraft skin on which ice may form. However, it is not practicable to install hot-air ducting to all parts of an aircraft, and electrical heating is adopted for the less accessible positions and where the heat requirement is relatively small. On most aircraft the largest single electrical heating load is for de-icing. Ice forms mainly on the leading edges of wings, tail planes and tail fin, and on propellers and around engine air intakes. Wing surfaces can often be heated by engine waste heat and on some aircraft the tail surfaces are heated by fuel-burning heaters, but nearly all aircraft use electrical de-icing for propeller blades and engine air intakes.

Electrical surface heating is effected by covering the surface with a resistance mat embedded in or fixed to an insulating base, and the mat is energized, either continuously (anti-icing) or intermittently (de-icing). Intermittent heating is adopted for those surfaces where the occasional formation of ice is not critical, in order to reduce the mean power required. The loading of de-icing and anti-icing mats varies with the position on the aircraft surface, being between 5 and 20 watts per sq. in. Large propellers, which are usually de-iced cyclically, require a total of 12 to 15 kW for the blades and spinner. Illustrations and a description of electrical de-icing systems are given in Chapter 12.

For windscreen anti-icing the resistive element must be practically transparent and colourless. Several types of element have been developed, the earliest of which consisted of fine wires embedded in the glass. Later methods use conducting films of stannic oxide or gold which are thin and cause little loss of transmitted light. Stannic-oxide films are usually of high resistance and a high supply voltage is required. A dissipation of about 6 watts per sq. in. is necessary. Windscreen demisting can be achieved with the same kind of element operated at only 2 or 3 watts per sq. in. In many installations the windscreen temperature is measured by a temperature-sensing element buried in the glass, and a control circuit is used to maintain the screen at a preselected temperature. A novel application for windscreen heating has arisen since it has been found that the impact strengths of some types of safety glass are increased at slightly elevated temperatures. Higher strength is particularly desirable at take-off to minimize the risk of damage from impact with birds. An optimum temperature of 50 deg. C. has been quoted for one type of laminated glass.

Electrically operated catering equipment is now in use on aircraft. Fig. 9.7 shows the galley equipment of a B.O.A.C. "Britannia", all of which is powered from a 112-volt d.c. supply. The urn has a loading of 2 kW, holds 2 gallons and weighs 17·5 lb. It is fitted with a two-heat control and a boil-dry cut-out. The six $1\frac{1}{2}$ gallon hot-beverage containers each have a loading of only 120 watts and weigh 10·4 lb. The heaviest load arises from the two ovens used for heating meals. These each have thermostatically controlled 3 kW

FIG. 9.7. *Galley equipment of a B.O.A.C. "Britannia": A, 2-kW urn; B-B, six 120-watt hot-beverage containers; C, 3-kW air-circulation oven.*

elements and air-circulating fans driven by 120-watt motors. Other catering equipment includes boiling plates, grill boilers, heated cupboards, saucepans, frying pans and coffee percolators. Water heaters for toilet use are usually of about ½ gallon capacity with a thermostatically controlled 500-watt heater.

Many small heaters are used for instruments. Gyroscopes, used in auto-pilots, are sensitive to temperature changes and it is convenient to maintain them at a constant temperature slightly above the maximum ambient temperature experienced in operation. Some atmospheric moisture-content detection heads use two heated surfaces, one of which is cooled by the moisture-laden air and the other by air which has been forced to change direction rapidly and is consequently practically moisture-free. The temperature difference of these two surfaces is related to the air moisture content. In most cases the small heaters of this type are supplied with low-voltage d.c. because low voltages are most convenient for small windings. Where on-off control is required, as in the gyroscope, a.c. may be preferred because the contact separation of the controlling switch can be smaller. In some instruments, however, a.c. heaters are avoided because of interference arising in the signal circuits. Small three-phase heaters are unusual because of the additional wiring, terminals and switch contacts required. Electrically heated clothing is occasionally required for special flights and heated bags have been developed for the comfort of military casualties.

All heating equipment can be designed to use a.c. power at any frequency and engine-driven three-phase a.c. generators are generally used to provide power for de-icing and anti-icing systems. Some of the heavier galley loads use three-phase a.c. but most smaller loads use d.c. power.

MOTORS

Aircraft electric motors are designed for minimum weight, but because they are dispersed throughout the aircraft they cannot usually be provided

with air-blast cooling. Many motors are required to operate only for a short time during each flight, and ratings between 15 and 90 seconds are common. After operation at the rated load for the specified maximum period, a cooling period of as long as 10 to 20 minutes may be necessary. These motors are usually enclosed and depend mainly on their thermal capacity to limit the maximum temperature to a safe value. Continuously rated motors are often fan-cooled.

Operating speeds are high and reduction gearing is used where necessary, the combination of a high-speed motor and gearbox being lighter than a low-speed motor. To minimize equipment weight, motors are often "built-in", the frame of the motor being integral with the equipment. Examples are to be found in fuel pumps, motor generators and actuators. The latter form an important class of motor-driven equipment and will be considered later. Almost without exception motors are started by switching directly on to the line, thereby avoiding the weight of starting equipment.

Direct-current Motors. Most aircraft d.c. motors are predominantly series motors, the speed/torque characteristics of this type, as shown in Fig. 9.8, being such as to ensure reliable starting against friction or inertia when the motor is switched directly on to the line. Where it is possible for motors to run unloaded, shunt windings are added to prevent overspreading. With a suitably designed motor, a shunt winding assisting the series winding can also do much to make the motor speed less sensitive to changes of load.

Motors for engine starting are rated for periods between 30 and 90 seconds, the longer ratings being required for gas-turbine engines. They are series motors with shunt windings to prevent overspeeding where this is

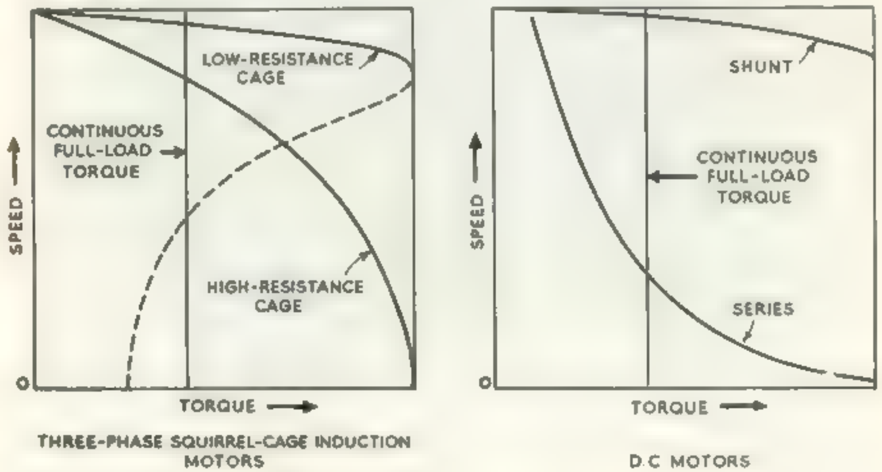


FIG. 9.8. *Speed/torque characteristics of various motors.*

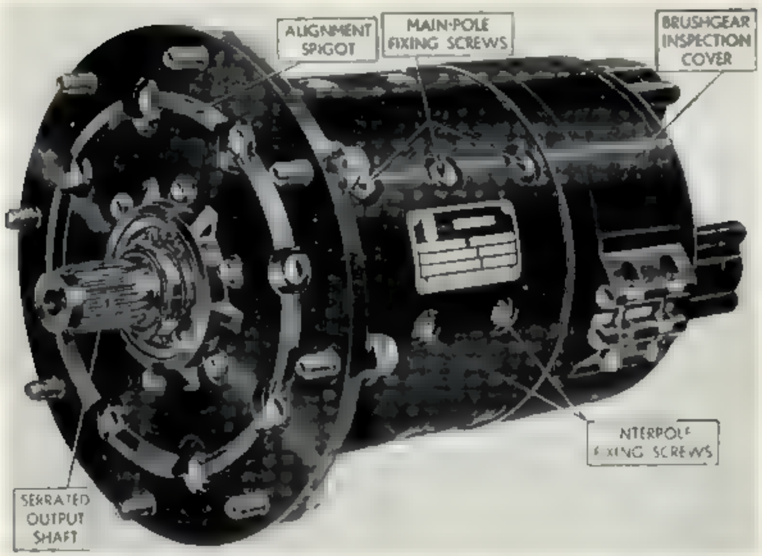


FIG. 9.9. *Gas-turbine engine starter motor (45 h.p.). Rating: 60 sec. Weight: 56 lb.*

considered necessary. Ratings extend up to 50 h.p., the larger motors having specific weights as little as 1·25 lb. per h.p. It is interesting to compare this figure with the specific weight of large generators which is rarely less than 6 lb. per kW or 4·5 lb. per h.p. Starter motors have lower specific weights because it is practicable to rate them for short periods. The design of starter motors resembles that of generators, the larger sizes having interpoles and compensating windings. The use of one machine to function both as starter and generator is periodically reconsidered but has not proved to be generally worth while. With commutation already a limiting factor in large d.c. generators, it is inevitable that the design compromises, and radical changes of operational mode incurred by the dual function render the combined machine a marginal proposition. A large 112-volt starter motor designed for a gas-turbine engine is shown in Fig. 9.9 and a 24-volt starter motor for a piston engine of up to 800 h.p. is shown in Fig. 9.10. In the latter case, a reduction gearbox and overload clutch are integral with the starter motor and provision is made for hand cranking. Starter-motor gearboxes have also been developed to enable the motor to be used for driving a hydraulic pump for propeller pitch changing. This operation occurs occasionally during flight but requires considerable power.

Gas-turbine engines, because of their greater inertias and higher starting speeds, make heavier and prolonged demands from the starter motor. For larger engines it is necessary to use resistance starting and, to relieve the pilot,

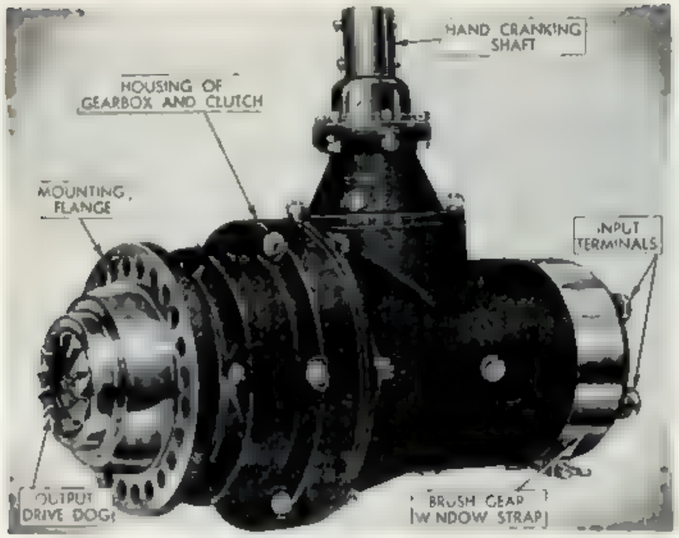


FIG. 9.10. *Starter motor (2·4 h.p.) suitable for piston engines up to 800 h.p.*

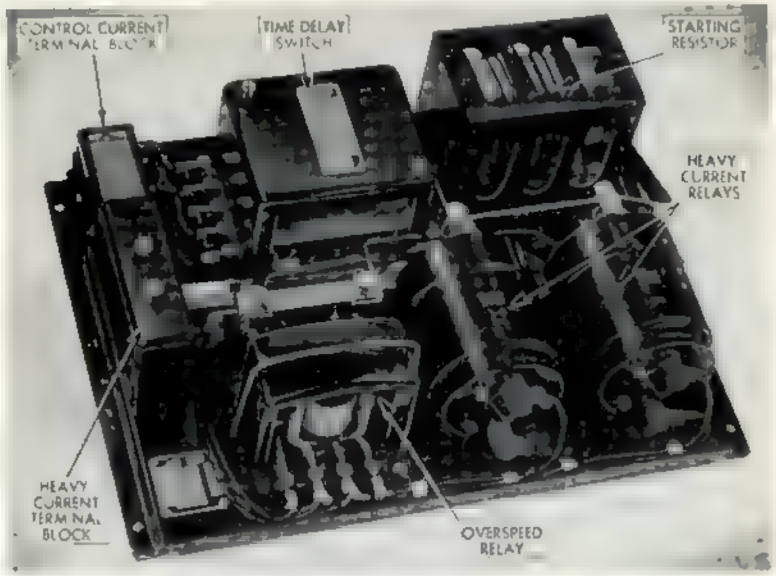


FIG. 9.11. *Automatic resistance starter panel for gas-turbine engine starter motor. The heavy-current strip conductors mentioned in Chapter 10 (see* Solid Conductors*) are shown at the centre of the illustration.*

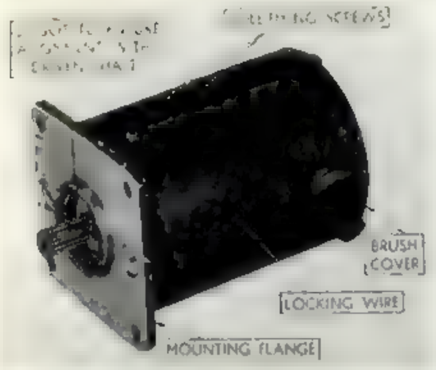


FIG. 9.12. *Two-pole d.c. motor capable of 0·13 h.p. output for 1 minute.*

the starting sequence has usually been automatically timed and controlled. A simple automatic resistance starting panel is shown in Fig. 9.11.

For general purposes a wide range of small d.c. motors is available. Fig. 9.12 shows a 1·5 in. diameter motor rated at 0·13 h.p. for 1 minute. It is of the split-series-field type (described later) and it weighs 0·72 lb. and operates at 20,000 r.p.m. A similar motor fitted with a clutch and brake is shown in Fig. 9.13. The clutch and brake is optional for most of the series of motors in Figs. 9.12 to 9.16 and is shown diagrammatically in Fig. 9.17. When the coils are not energized the spring-loaded driven disk is held against a friction brake lining by spring pressure. The motor output shaft is locked and the motor is disengaged. When the motor is switched on, both windings of the mechanism are energized and the driven disk is magnetically locked to the motor drive disk, the output shaft being simultaneously released. The principal purpose of the mechanism is to give rapid deceleration of the output shaft at switching off, by uncoupling the high-speed, high-inertia armature and braking the output shaft.

Another feature of the motor shown in Fig. 9.13 is a thermal protector which is sensitive to both armature current and motor temperature and which disconnects the motor if either of these quantities exceeds safe limits. A continuously rated motor having an output of 0·066 h.p. at 4,600 r.p.m. is shown in Fig. 9.14. Although totally enclosed, this motor is fitted with a

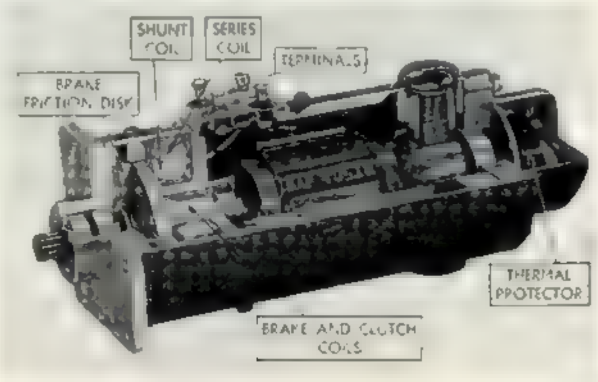
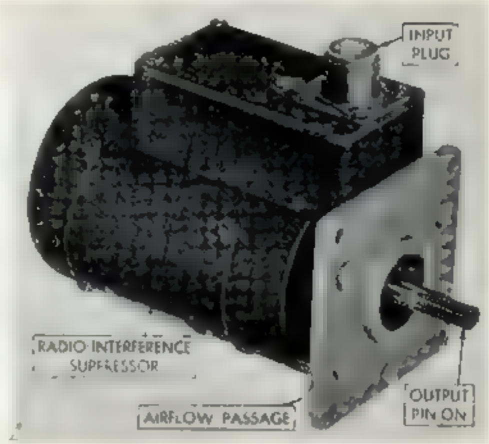


FIG. 9.13. *Small d.c. motor with built-in lutch, brake and thermal protector.*

FIG. 9.14. *Direct-current motor rated for a continuous output of 0·066 h.p. at 4,600 r.p.m. Weight: 2·5 lb.*



cylindrical jacket so that a cooling air flow can be directed over the outside surface of the stator. The weight of the motor, including its radio-interference suppressor, is 2·5 lb. A larger four-pole motor rated at 0·57 h.p. for one minute is shown in Fig. 9.15. Its full-load speed is 9,000 r.p.m. and its weight, including clutch and brake, is 5·2 lb. A continuously rated motor, 3·6 in. diameter over the stator air jacket, is shown in Fig. 9.16. It can deliver 0·38 h.p. and its weight is 6·5 lb.

Fractional-horsepower motors such as these rarely employ any special aids to commutation. The brushgear position is usually adjustable, but for reversible motors, where brush shift cannot be used, interpoles are occasionally used. In reversible motors the brushgear is usually positioned to give the same operating speeds in each direction. Split-pole construction is sometimes used to minimize the effects of armature reaction. This is illustrated in Fig.

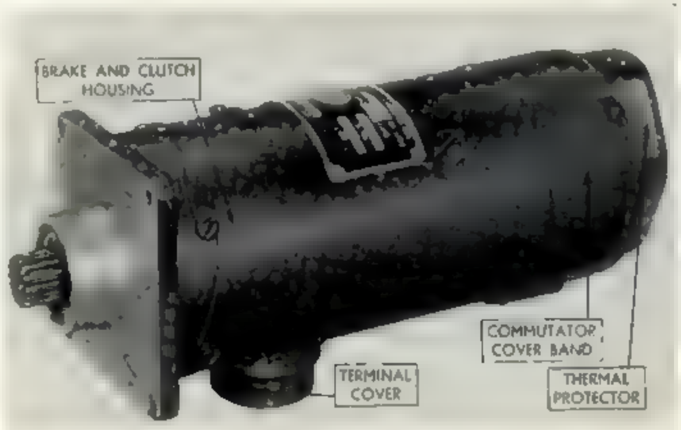


FIG. 9.15. *Four-pole d.c. motor rated at 0·57 h.p. for 1 minute. Weight: 5·2 lb.*

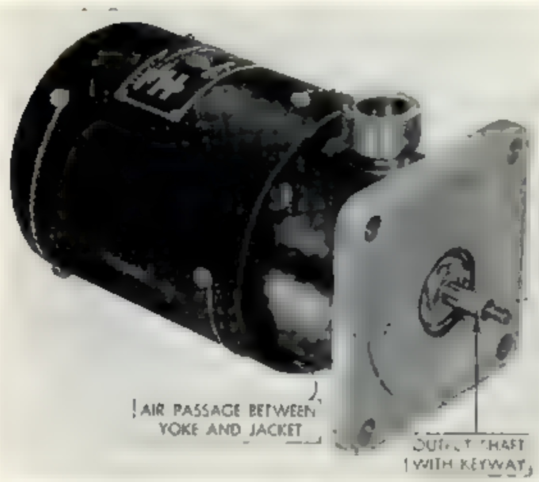


FIG. 9.16. *Totally enclosed 0·38 h.p. d.c. motor fitted with a cooling air jacket.*

9.18, which shows a lamination for a two-pole machine having split poles. The split is in such a plane that the field flux is practically unaffected but a relatively high reluctance path is offered to armature reaction flux.

Associated with most reversible drives, but not to be confused with split-pole construction, is the split-field motor. This is a motor having two electrically separated field windings used to establish flux in opposite directions. The reversible motor uses one of the two windings for each direction of rotation. This might appear to lead to an unnecessarily heavy motor but it has the advantage of enabling a split-series-field motor to be reversed with only a single-pole double-throw switch. Fig. 9.19 shows the connexions for reversing and stopping such a motor. In installations where the reversing switch is remote from the motor the saving in cable may be considerable and these advantages generally outweigh the disadvantage of the extra winding in the smaller motors. Larger motors are usually remotely controlled by a contactor. In these cases the split-field motor offers no saving in cables

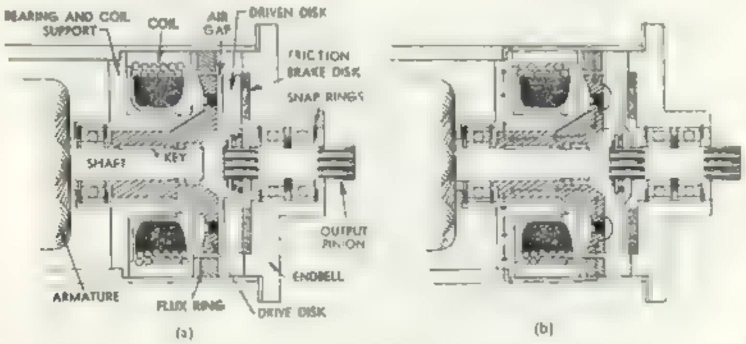
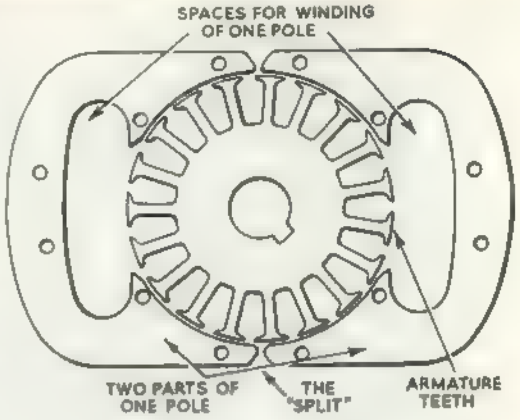


FIG. 9.17. *Electro-magnetic brake and clutch for fractional-horse-power d.c. motors:* (a) *motor off;* (b) *motor on. Arrows indicate the flux paths.*

FIG. 9.18. *Laminations of a two-pole rotary transformer using split-pole construction.*



and it is often preferable to use a more elaborate contactor to reverse the connexions of the series field winding of a normal series motor.

Fuel pump motors are totally enclosed and often designed for operation immersed in fuel. Other designs employ cooling jackets through which the fuel is passed. They are predominantly series motors having ratings up to about ⅓ h.p. and drive pumps which deliver up to 1,000 gallons of fuel per hour at about 10 lb. per sq. in.

Special-purpose motors with built-in brakes and clutches are occasionally used. An example is shown in Fig. 9.20 of a reversible motor rated at 9 h.p. for 45 seconds. The brake is electro-magnetic, operated by the motor current. The brake shoes may be seen bearing under spring pressure on the inside surface of the brake drum. When the motor is switched on the current passes through the strip-wound brake coil, energizing the brake magnet and releasing the drum by withdrawing the shoes. Power is transmitted through the multi-plate friction clutch to the output shaft which carries the brake drum. With this arrangement the clutch, in addition to protecting the motor by slipping in the event of a locked drive, can be set to assist deceleration of the drive by slipping when the brake is applied.

One of the advantages of d.c. motors is that their speed is easily controlled and it is curious that very few aircraft applications utilize this feature. Minor adjustments are sometimes made to the shunt field currents of converting machines to correct for small deviations from the design speed. A few

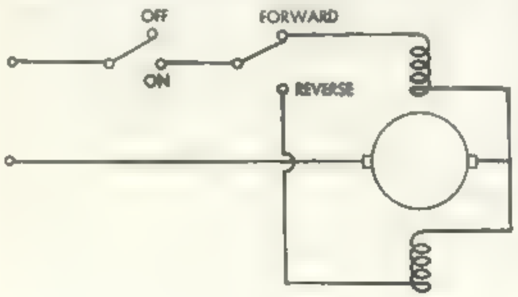


FIG. 9.19. *Connexions of a split-series-field motor.*

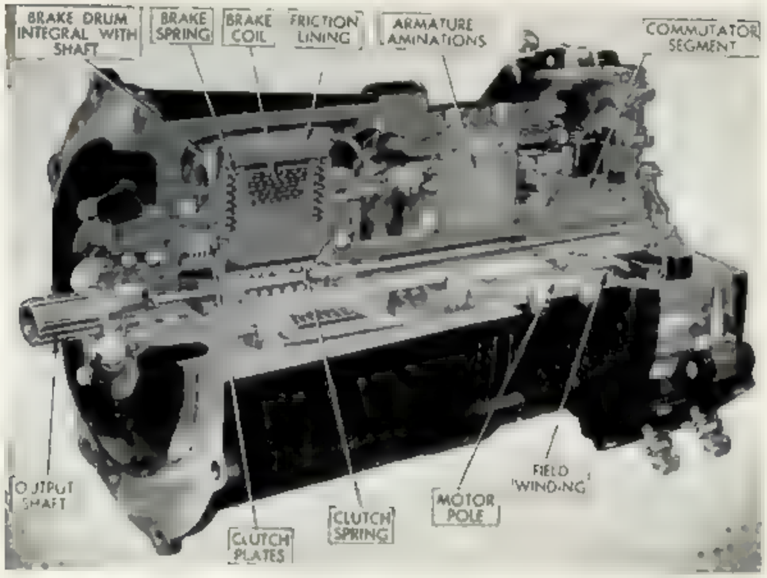


FIG. 9.20. *Reversible motor (9 h.p.) with built-in brake and clutch. Weight 26 lb. Rating: 45 seconds.*

converting machines have been fitted with speed regulators consisting of a pair of centrifugally operated contacts which are connected in parallel with a shunt-field resistor. Other convertors, usually those having a.c. outputs, employ more refined speed regulators for which an electrically separate auxiliary shunt-field winding is usually provided. Wide-range speed control has, however, been confined almost entirely to small motors used in instruments, such as bombing computers, and these have mostly been of a split-field type. In most cases the field windings are energized differentially from the push-pull output stages of electronic amplifiers. To suit the high voltage, low current output of such amplifiers the windings have many turns of fine wire.

Permanent magnets are used for motor fields, mostly in very small-sized motors where the armature power is small enough to be easily controlled. As in permanent-magnet a.c. generators, the magnets are usually stabilized to avoid demagnetization. This is most likely to occur if the armature supply is reversed suddenly when the motor is operating at full speed. Stabilized magnets also permit a short-circuit to be applied to the armature, while the motor is rotating, in order to provide dynamic braking.

Alternating-current Motors. Those features of the three-phase induction motor which have brought about its universal adoption also promise it a future in aircraft. At present its use is restricted because many aircraft do not

have constant-frequency a.c. supplies, but in aircraft having suitable supplies it performs many tasks which would otherwise have been carried out by d.c. motors. Fig. 9.8 compares the speed/torque curves of several motors and is intended to show that induction-motor characteristics can be made to resemble those of either shunt or series d.c. motors. Most industrial squirrel-cage induction motors have low-resistance cages giving speed which is practically constant over the working range. In this respect they are almost identical with d.c. shunt motors. However, if a cage of higher resistance is used the speed/torque curve is modified, as shown, to give speed which falls rapidly as the load torque is increased. The effects of cage or rotor resistance are discussed in most electrical engineering text-books, such as in Ref. 5. The curve shown in Fig. 9.8 for an induction motor with a high-resistance cage is for the case in which rotor resistance is equal to rotor reactance at the supply frequency. This characteristic has two features common with that of the d.c. series motor, speed falling rapidly as the load torque is increased and a starting torque considerably in excess of normal full-load torque.

Many d.c. series motors can be satisfactorily replaced by induction motors having rotor cages of materials of higher resistance than that of copper or aluminium, such as brass or phosphor bronze. In applications requiring very high torques for limited periods, however, induction motors are at present inferior to d.c. series motors. These applications include engine starting and the driving of hydraulic pumps which are intermittently loaded. For ratings of more than about half a minute the d.c. motor cannot be operated at maximum available torque without overheating, and the a.c. motor is superior.

Supplies of varying frequency are being used for induction motors where speed is not important. If the frequency variation is large it is usual to arrange that the supply voltage varies in sympathy. This is necessary in order to maintain the output torque at higher frequencies, and to avoid excessive current at lower frequencies. Such a supply, having varying voltage and frequency, is unsuitable for most other equipment and does not secure a constant motor speed; it merely ensures that the motor operates at rated torque and current. Its applications are therefore limited.

At present the most popular motor for 400 c/s supplies is one having four poles and hence a maximum speed a little less than 12,000 r.p.m. A two-pole motor operating at nearly 24,000 r.p.m. might be slightly lighter but some difficulties are experienced with grease-packed bearings at such high speeds and for most purposes extra speed-reduction gears would be necessary. A range of aircraft induction motors, including both totally enclosed and ventilated types, is shown in Fig. 9.21 and Fig. 9.22. Brakes, performing the same function as on d.c. motors, are available for a.c. operation but have been less widely used. Like a.c. solenoids, a.c. brakes present more

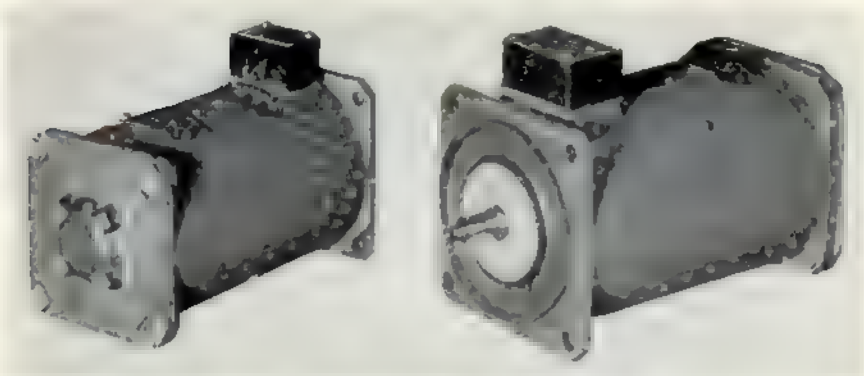


FIG. 9.21. *Two views of a representative type of totally enclosed motor with keyed drive shaft* (right); *some types have a pinned shaft. The housing of the ball-bearing* (left) *is packed with high-melting-point grease.*

design problems than their d.c. counterparts and are usually larger and a little more elaborate. One type of brake, called a split-phase type, employs two windings, each connected in parallel with one of the three motor windings. This is one method of ensuring that the braking force is never zero.

Two-speed a.c. motors have occasionally been used. One such motor is shown in Fig. 9.23 in which the two speeds are obtained by the use of two sets of stator windings. These are four- and six-pole windings giving speeds of 12,000 and 8,000 r.p.m. respectively. This particular motor has been

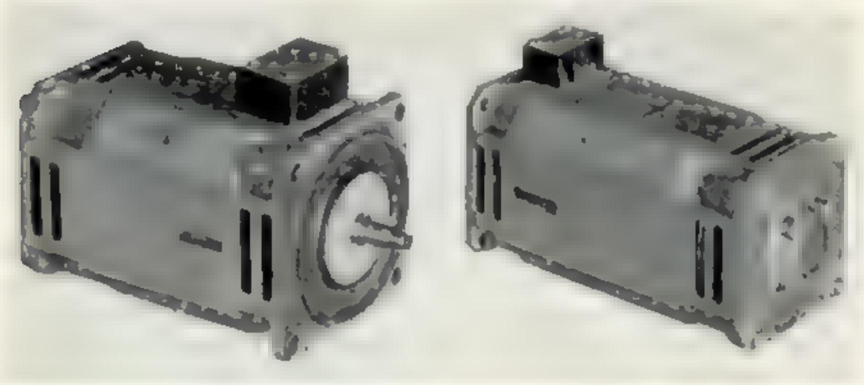
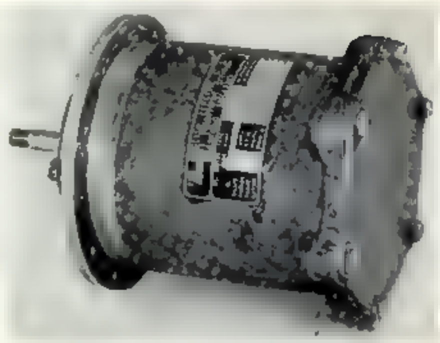


FIG. 9.22. *Three-phase, 400 c/s, four-pole induction motor representative of a range extending from 0·005 to 20 h.p. This is an open-type motor, the ventilating slots being clearly seen. It has a keyed drive shaft.*

FIG. 9.23. *Two-speed a.c. motor designed for driving a fuel pump, and for cooling by immersion in fuel.*



designed to deliver substantial outputs at the synchronous speeds, probably by using a rotor shaped to give salient magnetic poles. It was used initially as a fuel-pump motor on the Avro "Vulcan" where a number of pumps, feeding a common line, were operated at 8,000 r.p.m. while one other was operated at 12,000 r.p.m. Only the latter delivered fuel, but in the event of its failure the others were immediately able to provide adequate delivery pressure and flow for the engine. The motor is cooled by fuel immersion, the permissible temperature range of the fuel being −50 to +50 deg. C. It is, however, capable of running light without cooling for one hour.

Fig. 9.24 shows a sectional view of a two-pole fan-cooled motor. It is designed for a 260-cycle 110-volt three-phase supply, and is continuously rated at 5.6 h.p. The weight is 17·5 lb. (3·12 lb. per h.p.).

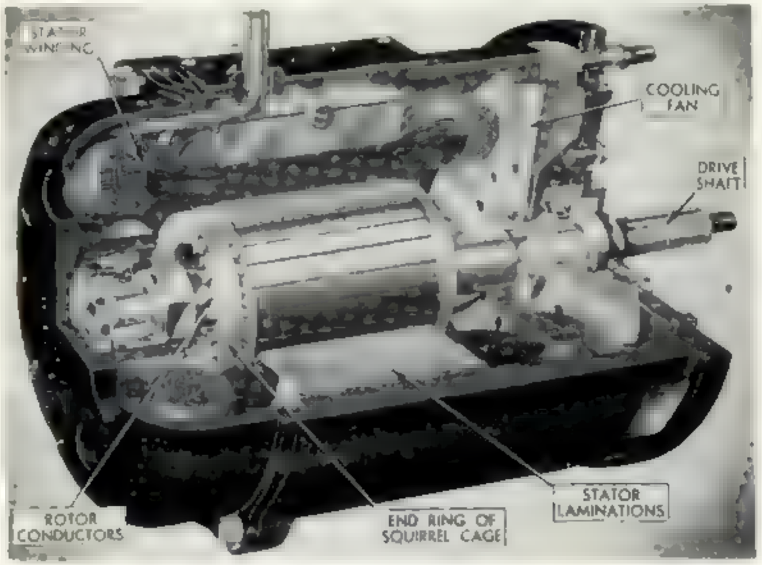


FIG. 9.24. *Fan-cooled, continuously rated three-phase induction motor, 110-volt, 260 c/s, 5·6 h.p. Note the stud locking pin at top right-hand of the illustration.*

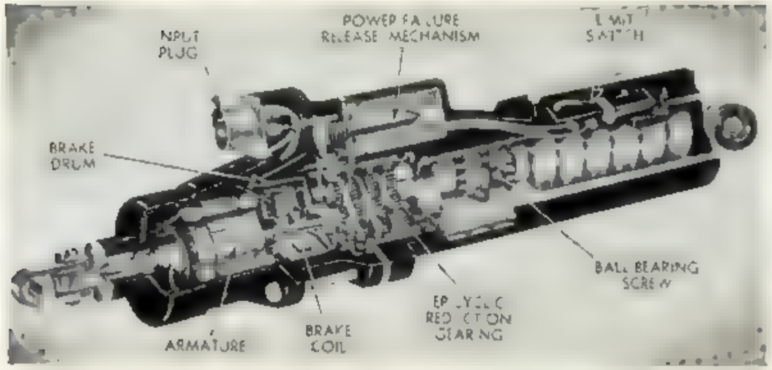


FIG. 9.25. *Linear actuator developing 2,500 lb. thrust or tension. Weight: 10·5 lb.*

Occasional requirements for synchronous a.c. motors have been met with hysteresis motors. These employ a stator similar to that of an induction motor but the rotor consists of a tube of permanent-magnet material which is magnetized by the stator m.m.f. During starting, slip occurs and torque is developed because the magnetic material is taken through its hysteresis cycle at the slip frequency. At synchronism the motor behaves like a synchronous motor with an electro-magnetic field system. Detailed information on hysteresis motors is given in Ref. 20.

ACTUATORS

An actuator is designed to perform limited rotary or linear motion; for example, 20 revolutions with an available torque of 10 lb.-ft., or a travel of one inch with an available force of 1,000 lb. A short-time-rated motor falls within this definition of an actuator, but general usage restricts the use of the name for mechanisms where the output is measured in terms of revolutions rather than in time. Actuators are made for industrial purposes but generally the industrial equipment is made up of separate units such as a motor, gearbox and brake. This arrangement facilitates inspection, servicing and repair. The reductions of volume and weight which can be achieved by integrating such units are, however, over-riding considerations in aircraft, and in consequence actuators are extensively used. Among the many applications are the operation of wing flaps, trim tabs, fuel-oil and air valves, bomb-bay and undercarriage doors; the raising and lowering of undercarriages, the control of air-intake openings, the adjustment of tail-plane incidence and the operation of dive brakes.

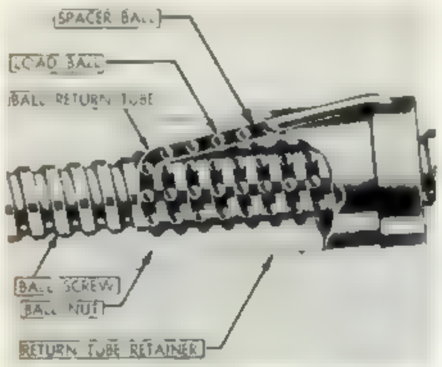
Linear Actuators. Actuators are available capable of developing thrust or tension of between 20 and 20,000 lb. The stroke is usually only a few

inches but can be as much as 20 in. and the operating time is a matter of seconds, rarely more than a minute. The smallest linear actuators have strokes of about 1 in. Applications requiring shorter strokes or smaller thrusts are usually met with solenoids, which are discussed later.

A typical medium-sized actuator is shown in Fig. 9.25. It has a normal thrust or tension of 2,500 lb. and a maximum of 3,300 lb.; its stroke of 3½ in. is completed in 38 seconds. The actuator is intended to be mounted as a link between the aircraft frame and some member which is to be moved, and the steel lug on the left-hand end is arranged to allow the freedom necessary for realignment of the actuator axis. The case is of aluminium alloy and is designed to carry more than three times the maximum rated thrust because actuators are sometimes subjected to forces greater than those which the mechanism can develop.

The mechanism consists of a motor at the left-hand end of the case, four stages of epicyclic reduction gearing near the middle, and a screw at the right-hand end. A single plate clutch is interposed between the motor and the gearbox and a brake is fitted to the shaft on the gearbox side of the clutch. The brake is released by motor current and is applied by spring pressure when the motor is switched off. It serves to prevent the actuator from being moved by an externally applied force and to minimize the overrun. The clutch is preset to a slip at a torque corresponding to slightly more than the maximum rated thrust, and this protects the motor and mechanism from extreme overloads.

The motor is of the split-series-field type to simplify the wiring and switch used to control the actuator. It is designed to operate from a 24-volt d.c.



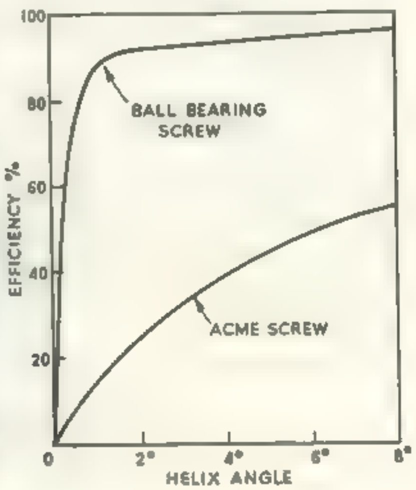


FIG. 9.26. *Ball-bearing screw, showing the space in which the balls circulate.* (Right) *Curves illustrating its superior efficiency.*

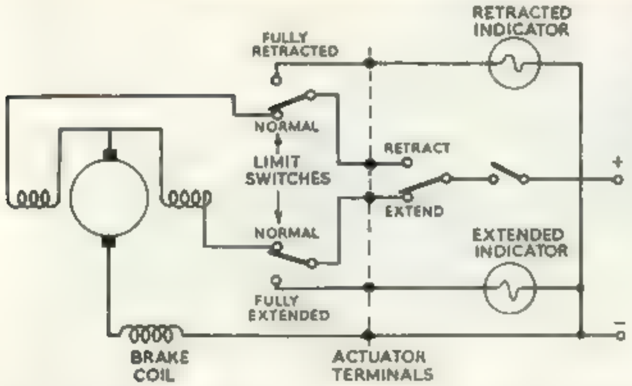


FIG. 9.27. *Wiring diagram and connexions for a linear actuator with extreme-position indicator lamps. Note that the limit switches are at "normal" except when the ram is at extreme positions.*

supply at a full-load current of 9 amp. and is rated for $3\frac{1}{2}$ minutes. It is a high-speed motor having a relatively low specific weight, the combination of high-speed motor and reduction gear being much lighter and smaller than a motor capable of driving directly. The screw converts the rotary motion of the output gear shaft to the linear motion of the ram. It is a ball-bearing screw which may be considered as a normal screw from which the thread has been removed and replaced by steel balls. Fig. 9.26 shows a part-section of such a screw in which the path of the balls may be followed; the graph compares the outstandingly high efficiencies of ball-bearing screws with those of Acme screws. Conventional screws of such forms as Acme and truncated Whitworth are also used in aircraft actuators, but except in small actuators where efficiency is of less consequence, the ball-bearing screw is being increasingly adopted.

Fig. 9.27 is an internal wiring and external connexion diagram for a similar actuator. The external switches enable the actuator to be stopped or started at any point in its travel and the limit switches ensure that the motor is switched off just before the ram reaches the limit of its travel. The positions of

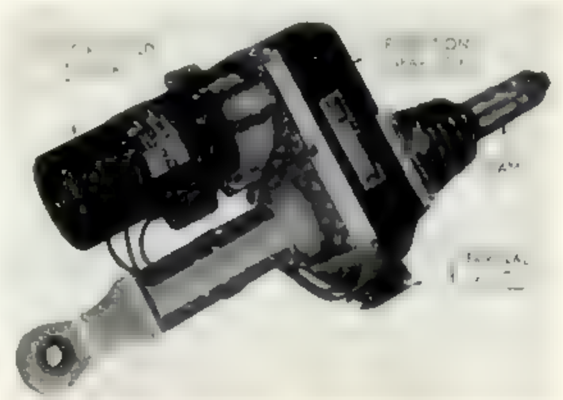


FIG. 9.28. *Linear actuator, of German manufacture.*

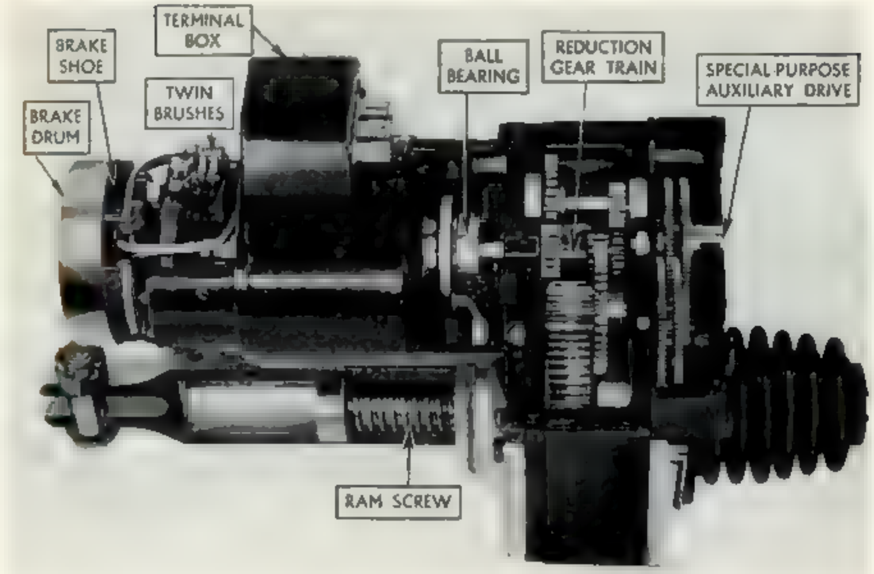


FIG. 9.29. *German actuator sectioned to show reduction gear train and ram screw.*

these switches, which are shown in Fig. 9.25, are adjustable to enable the ram travel to be predetermined within the extreme limits. Fig. 9.27 shows additional contacts on the limit switches being used to operate lamps which indicate that the ram is in one of the two extreme positions. Systems for continuous ram position indication are occasionally required. These are usually d.c. systems having, built in to the actuator, some form of position transmitter, such as a simple potentiometer, the wiper of which is coupled to the ram.

An additional device, not fitted to all actuators, permits movement of the ram by an externally applied force of 170 lb. in the event of a power failure. Movement is normally prevented by the spring-operated brake and, in some actuators using Acme screws, by the self-locking action of the screw. This power-failure-release device consists of a solenoid-operated pawl which engages and locks the annulus of the first epicyclic reduction gear, only when the solenoid is energized.

The actuator shown in Fig. 9.28 is of side-by-side construction having the motor alongside instead of in line with the ram. This construction is useful where a short actuator is required and where the thrust is very large since the motor and gearing are outside, instead of within, the load-carrying members. The actuator shown is of German origin and was fitted to a

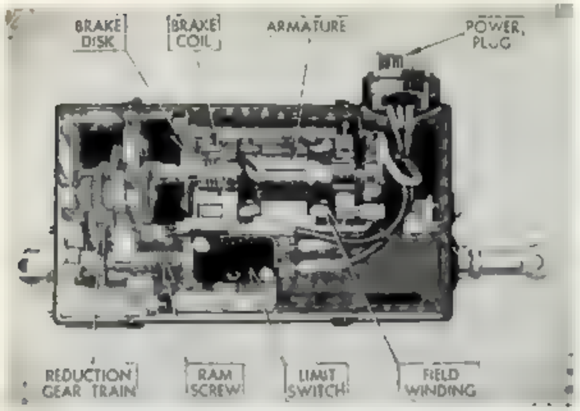


FIG. 9.30. *Small "side-by-side" linear actuator of modern design.*

Focke-Wulf 190 during the second world war. A sectioned view of the motor and spur reduction gearing of a similar but slightly larger actuator is shown in Fig. 9.29. The brake, at the non-drive end of the motor, is a rotating drum with four internally expanding shoes. The motor is a split-series-field motor. It uses split-pole construction and twin brushes to improve commutation. Motor speeds are 14,000 and 8,500 r.p.m. for the small and larger actuators respectively. Neither actuators have clutches or built-in limit switches.

A modern side-by-side actuator is shown in Fig. 9.30. It completes a stroke of 3 inches in 28 seconds at a normal load of 50 lb. Its power consump-

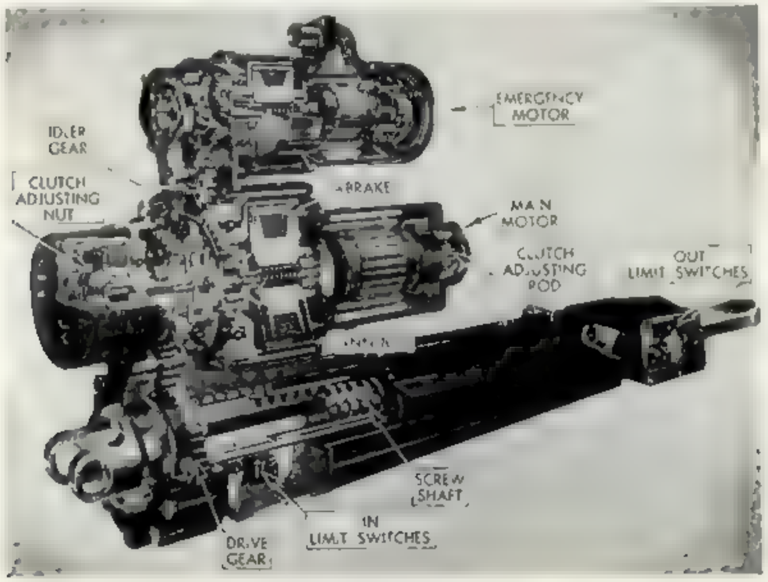


FIG. 9.31. *Large 112-volt d.c. linear actuator with a built-in emergency motor.*

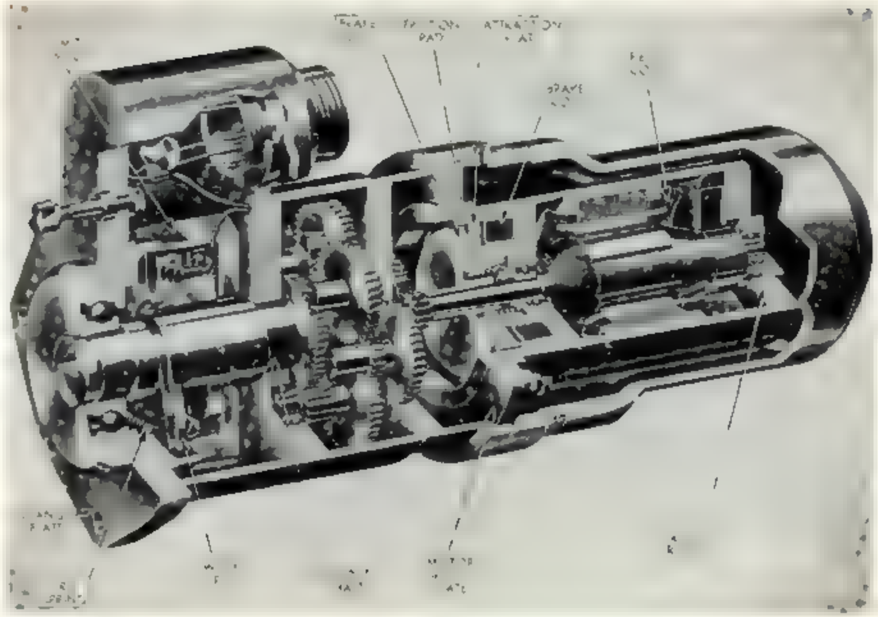


FIG. 9.32. *Small rotary actuator for operating hydraulic valves and fuel cocks.*

tion is $1\frac{1}{2}$ amp. at 25 volts and its weight is 2 lb. 6 oz. A very large side-by-side actuator, such as could be used to operate the undercarriage of a large aircraft, is shown in Fig. 9.31. As a safety measure this actuator has an emergency motor which is normally inoperative, but if required it can operate the ram at the same load as the main motor although at reduced speed. The maximum thrust is 3 tons, the stroke $18\frac{3}{4}$ in. and its weight is 75 lb.

Overall efficiencies of actuators are between 10 and 35 per cent, the higher values being attained only with the larger actuators. Since they are operated only for very short periods low efficiencies are not very important. Some of the smallest actuators use permanent-magnet-field motors. A typical example is an English Electric actuator which develops a thrust of 30 lb. over a stroke of 1 in. It is enclosed in a light alloy case $1\frac{1}{2} \times 2\frac{1}{2} \times 3\frac{1}{4}$ in. and weighs $15\frac{1}{4}$ oz. The motor is 1 in. diameter.

Actuator components, such as motors, gearboxes, jack screws and control units which may be assembled in different combinations, are offered by some manufacturers. Control units include limit switches, position indicators and radio noise filters. This scheme has several advantages such as availability of a wide range of different actuators from a relatively small stock of components. It is also useful in development because it permits changes of performance to be made easily should the initial choice prove unsatisfactory.

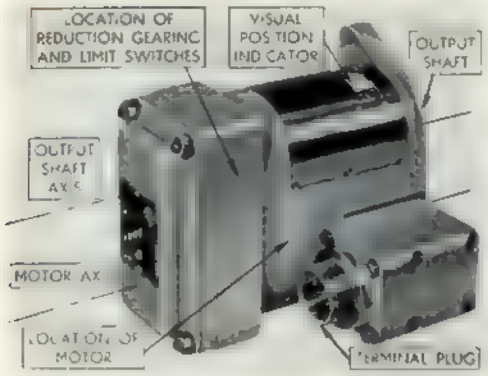


FIG. 9.33. *Rotary actuator with visual indication of position of output shaft.*

Rotary Actuators. Actuators are available with output torques of from one to several hundred lb.-ft., and with output speeds of from one to several hundred r.p.m. Output shaft rotations are restricted to as little as 90 deg. for such functions as fuel-cock operation, or completely unrestricted, in which case there is nearly always an operating time limit of less than about 3 minutes. Actuators having restricted angular output are often rated for a number of successive cycles of operation, usually about six, after which a cooling period is necessary. Continuously rated rotary actuators are only occasionally required.

A sectioned view of a typical fuel-cock actuator is shown in Fig. 9.32. This actuator can be preset to give up to 90 deg. rotation at a torque of nearly 2 lb.-ft. and can complete 90 deg. rotation in about 3 seconds. It is powered by a split-series-field motor operating at 13,000 r.p.m. and rated at 0·2 h.p. for 1 minute. A spring-loaded disk-type brake, released by the motor current, is carried on the motor shaft and between the motor and the output shaft is a spur gear train, reducing speed in the ratio 2,857 to 1. An extension of the actuator case around the output shaft accommodates limit switches, a connector plug and, in some models, a visual indication of the output shaft position. The actuator weighs 2 lb. Two actuators of similar performance and weight but of different construction are shown in Figs. 9.33 and 9.34.

A large rotary actuator is shown in Fig. 9.35. Unlike those previously described this has no restriction on the angle of rotation

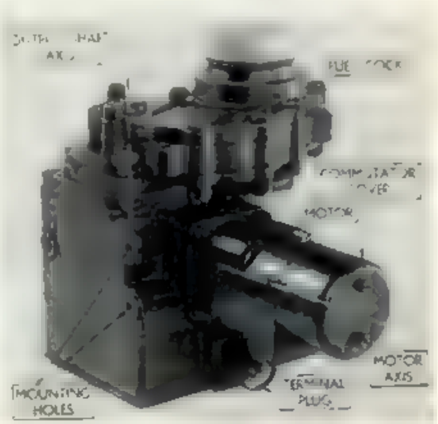


FIG. 9.34. *Rotary actuator fitted to a Vickers Type R 1½-in.-bore fuel cock.*

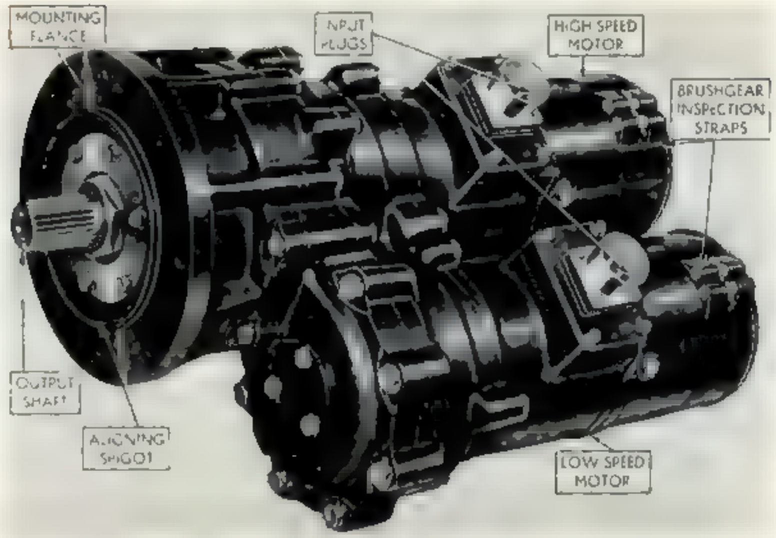


FIG. 9.35. *Two-speed rotary actuator employing two separate motors.*

of the output shaft but it would normally be operated only for limited periods. It is a two-speed actuator, one motor only being used at each speed, 115 and 50 r.p.m. The normal low-speed torque is 250 lb.-ft. and the maximum available is 375 lb.-ft. The actuator is operated from 112 volts d.c. and weighs 43 lb. By using two motors a degree of security is obtained against motor failure.

A rotary actuator employing two motors both of which are normally in use is shown in Fig. 9.36. It was designed for raising and lowering bomb-bay air deflector plates. The two motors drive the output shaft through a gearbox containing differential gearing. This operation with one motor out of service is automatically obtained at normal torque, which is 87½ lb.-ft. but at 76 instead of the normal 156 r.p.m. The actuator is designed for operation from a 112-volt d.c. supply at a full-load current of 16 amp. It weighs 31 lb.

Actuator Operating Conditions. Owing to the fact that many actuators are operated only occasionally during flight, and also because they are dispersed throughout the aircraft, particular attention has been given to ensuring satisfactory starting and operation over wide temperature ranges. A typical range has been −40 to +90 deg. C. but more recent equipments have been proved at temperatures as low as −75 deg. C. and as high as +150 deg. C. Satisfactory operation over fairly wide voltage ranges is also a feature of many actuators, particularly those designed for 28-volt d.c. systems. A voltage of 18 to 29 volts has been frequently specified to cover the extremes of operation from a partially discharged accumulator, making allowance for

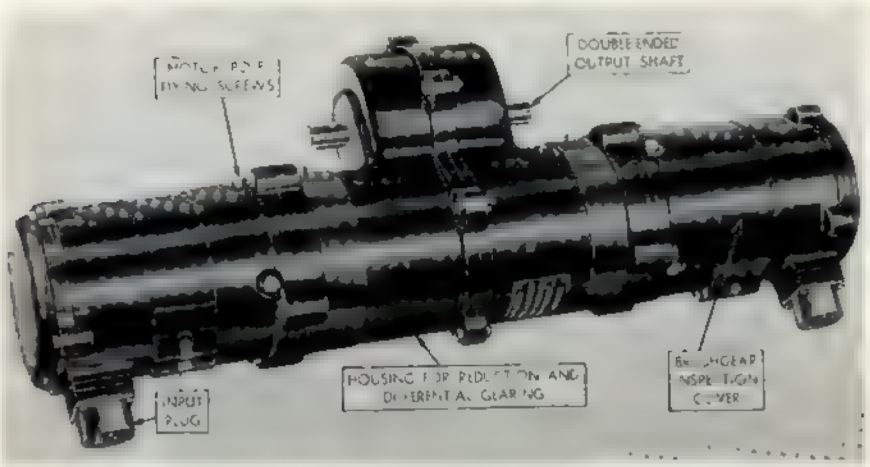


FIG. 9.36. *Rotary actuator fitted with two motors. Rated output 88 lb.-ft. at 156 r.p.m. Weight: 31 lb. The design allows for normal torque with only one motor operating, but at reduced speed.*

some cable volt drop, and operation from a system with generators giving slightly higher than normal voltage.

Servicing. The setting and checking of limit switches, clutches and brakes is almost invariably carried out on a test bench. Only minor checks on such things as tightness of electrical connexions, external nuts and screws are normally carried out *in situ*. On larger actuators brushgear is also accessible. These minor checks are specified after about 250 hours of flying time and major checks after about 750 hours.

Geared Motors. A number of manufacturers offer motors with integral reduction gearboxes and sometimes also with built-in clutches and brakes. The distinction between a motor with these accessories and a rotary actuator is indefinite. Ratings in excess of a few minutes are very unusual for actuators but not uncommon for geared motors. Unlike actuators, which usually have output speeds of less than a few hundred r.p.m., geared motors frequently have output speeds of several thousand r.p.m. These higher output speeds are intended for direct drives to such things as hydraulic and pneumatic pumps.

SOLENOIDS

Solenoids providing linear movement of up to ½ in. are used for locking mechanisms, to prevent accidental operation or operation by externally applied forces. Typical are locks for undercarriages and flaps. Unlike an actuator which develops approximately constant thrust or tension over its stroke, a solenoid usually develops maximum tension only when the plunger

is fully retracted. It is incapable of developing thrust and is returned to the extended position by a spring. Since the spring pressure is always present, a high extending force can be obtained only at the expense of the retracting force. A typical solenoid, weighing about 1 lb., exerts a tension rising from 5 to 10 lb. over a ½ in. stroke and has a return force of only a few pounds. Larger solenoids are little used because actuators can give much greater forces and strokes than solenoids of the same weight.

Alternating-current solenoids are possible but are heavier than d.c. solenoids, usually by 25 per cent or more. This arises from several things. A simple a.c. solenoid has an alternating flux and periodically both the flux and the operating force are reduced to zero. This is often countered by fitting the magnet with a shading coil, a single-turn short-circuited coil which encloses part of the cross-section of the magnetic circuit somewhere near the air-gap. The coil delays the flux cycle within its circumference and a two-phase flux system is set up so that the mean value of air-gap flux is never zero. Alternating-current solenoids are also at a disadvantage because of eddy-current and hysteresis losses. The former are minimized by using a laminated magnetic circuit and the latter by choice of material and operation at moderate flux densities. Chattering and audible humming are defects to which a.c. solenoids are liable. With the small germanium and silicon rectifiers now available it is likely that, in all cases where it is necessary to use a.c. power for solenoid operation, it is better to use individual rectifiers and a d.c. solenoid. This is certainly true if the a.c. power is not at constant frequency.

Rotary Solenoids. These have been developed to operate rotary switches. The principle of the rotary solenoid is shown in Fig. 9.37. The plunger is arranged to apply forces, via steel balls, to several inclined planes which are positioned on a circular track perpendicular to the output shaft axis. The rotation occurring at each solenoid operation is limited, in practice to about 60 deg., but a ratchet mechanism can be attached to the output shaft to give continuous stepped rotation. This may be automatic if suitable contacts are fitted to the mechanism, or may be controlled by switching the solenoid. A mechanical refinement, which enables the solenoid characteristic of increasing tension with plunger retraction to be utilized to give constant output torque, is the use of inclined planes of changing slope.

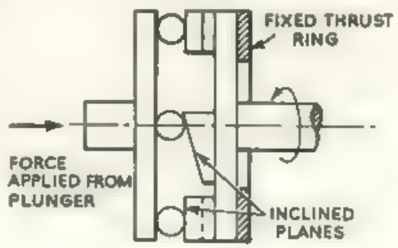


FIG. 9.37. *Illustrating the principle of a rotary solenoid.*

Torque Motors. These are motors which provide torque over very limited angular rotation and have been developed for operating small hydraulic valves in servo-controlled systems. A typical torque motor gives a deflection of about 5 deg. either side of the normal position and develops a maximum torque of about 0·1 lb.-ft. The rotor is made of soft magnetic material, carries no windings and is free to rotate between mechanical stops. The stator carries control windings and either excitation windings or permanent magnets. The control windings are usually arranged to suit a push-pull output stage of either an electronic or magnetic amplifier. Owing to its simple construction the machine can be made very robust and is inherently suited to aircraft and missiles. It is particularly useful in servo-controlled systems because it is capable of responding quickly to changes of control-winding current, certainly much quicker than a rotary actuator.

The name *torque motor* is also applied to devices producing very restricted linear movement but specially designed for hydraulic valve control in servo systems. Typical performance is a maximum displacement of 0·015 in. either side of the normal position, a maximum force of about 10 lb., and the ability to follow changes of control-winding voltage at frequencies up to a few hundred cycles a second.

RADIO, RADAR, NAVIGATIONAL AIDS AND INSTRUMENTS

These equipments mostly require low-voltage supplies for filaments and high-voltage supplies for valve anodes. The filament supplies may be either d.c. or a.c. although in some circuits a.c. may give rise to interference and a smoothed d.c. supply may be necessary. Direct utilization of 28-volt aircraft supplies for valve filaments has generally required the operation of filaments in series, a practice which is considered undesirable because changes occuring at one filament of the chain inevitably affect all the others. Series regulators of the carbon-pile type have been used in British aircraft in order to secure constant applied voltage to such filament chains, both under normal conditions when the generators are operating and also when the system is energized from the accumulator alone. It appears, however, that this measure may have been unnecessary since other countries have used direct connexion to the system busbars, apparently with comparable success.

Typical very-high frequency (V.H.F.) short-range transmitter-receivers have a total power consumption when transmitting of 500 to 600 watts, about 200 watts of this being used for filament heating.

Except by a few equipments which are designed to utilize the 28- and 112-volt aircraft supplies, high-voltage supplies are required for valve anodes, and so on. These are obtained from rotary transformers, usually having one or more outputs in the range 200 to 750 volts. Individual items of equipment have, in the past, had their individual rotary transformers, but the use of

supply units common to a number of equipments is becoming more attractive as the total load increases.

The availability of a.c. supplies enables the rotary transformer to be replaced by a static transformer and rectifiers. Some weight penalty is incurred if the supply is at variable instead of constant frequency, but a frequency range of 3 to 1 appears to be acceptable and enables the converting equipment to be lighter than that supplied from d.c. The elimination of the rotary transformer brings a substantial improvement in reliability and simplification of servicing. A further minor advantage of a.c. supplies is that the small cooling fans, commonly used in electronic equipments, can be driven by induction motors instead of d.c. motors. Transistor oscillator convertors can be used for deriving high-voltage d.c. from the standard aircraft d.c. supplies, but these are only practicable, at present, for outputs up to about 200 watts.

The total maximum loading of electronic equipment in a large civil aircraft is about 4 kW but not all the equipments are used simultaneously. The largest single item is usually the high-frequency transmitter, 3 to 30 Mc/s, which is used for long-range communication and has a maximum loading of about 2 kW. Military aircraft carry much more radar and electronic equipment, such as computers for bombing, than civil aircraft and have total maximum loadings of 6 to 10 kW.

Radar. Radar equipments have similar power requirements to radio but generally require rather higher d.c. voltages for transmitting circuits and display tubes. In some cases these voltages are outside the range for which rotary transformers can be satisfactorily designed and if an a.c. supply is not available the rotary transformer is used to provide a medium-voltage a.c. output which is subsequently transformed and rectified. On civil aircraft radar is used to give storm warning, and on military aircraft it has numerous applications such as the location of other aircraft, ground mapping, and so on.

Navigational Aids. These equipments have the same kind of power requirements as radio but at a fairly low level. Several navigational systems depend for their operation on ground equipment in which most of the high-power circuits are located. A large civil aircraft may require a maximum of about 1 kW.

Auto-Pilots. These have been designed for operation from both d.c. and constant-frequency a.c. and have loadings of about 500 watts.

Instruments. Under this heading is included such things as information transmitters for relaying pressures, positions, temperatures, etc., remote-reading magnetic compasses, and fuel gauges. Power requirements are always small and are either for d.c. or constant frequency a.c.

CHAPTER 10

Power Distribution and Control

ALTHOUGH distances in aircraft are small by comparison with distances encountered in other power systems, the cables in a large aircraft have a total length of more than 20 miles and account for a little more than 1 per cent of the all-up weight. They constitute the framework of the distribution system which carries power, in several different forms, controlled quantities and signals into every part of the aircraft. The system is not only required to operate reliably but must also be designed to present the minimum possible risk of fire and structural damage in the event of failure of any kind. These risks are minimized partly by choosing cables appropriate for the environment and duty, and partly by the installation of protective equipment, such as fuses, fault-sensitive relays and circuit-breakers, at strategic points in the system. Reliable functioning of the system is secured mainly by the design of the principal distribution feeders and busbars, and is assisted by the protective equipment. There is a danger, however, which has been exposed many times in practice, that the protective equipment installed to protect the aircraft may, through faulty operation or "nuisance tripping", unnecessarily deprive it of its electrical supplies.

CABLES

The two principal parts of aircraft cables are the insulation and the conductor. Insulation has undergone many changes in order to obtain better resistance to attack by fluids, high and low temperatures and mechanical damage, but in general, adequate insulating properties have always been easily obtained. The need for these improved properties seemed, for a time, to overshadow even the basic requirement of low weight. Conductor development has been mainly concerned with the uprating of copper conductors and the introduction of aluminium for larger cables.

Cable Insulation. Insulation is required to be tough over a fairly wide range of temperature, resistant to fuels, lubricants and hydraulic fluids, and practically non-flammable. It should be flexible to permit easy installation and the use of bends of small radii. It should be easily stripped from the

conductor, for terminating, and it should be suitable for use with crimped-on terminals. It should also have minimum weight.

Rubber-insulated cable was used initially, protected against oil by paint-impregnated cotton braid, and later against hydraulic fluids by cellulose lacquered braid. Embrittlement of the cellulose lacquer led to the adoption of a poly-vinyl-chloride (p.v.c.) protective sheath which was limited to an upper temperature of 70 deg. C. at which the p.v.c. softened. Rubber insulation became obsolete in the late 1940's with the introduction of polychloroprene (Pren). Pren is superior to rubber in several respects: (*a*) it is flame resistant (it can be charred by a flame but does not continue to burn when the flame is removed); (*b*) it is resistant to fuels, common lubricants and most hydraulic fluids; (*c*) it resists deformation at temperatures as high as 90 deg. C. yet remains flexible at −30 deg. C. It may be used, under moderate conditions of vibration, at temperatures as low as −75 deg. C.

Pren cables are also insulated with glass-fibre braid between the tinned-copper conductor and the Pren. This is primarily to provide a noncombustible layer, sufficient to enable the cable to continue functioning even after the Pren has been completely charred. Pren itself is not so good an electrical insulator as many other dielectrics, such as rubber and polythene, but at the relatively low voltages of aircraft power systems this is of no consequence. Some improvement in insulation resistance is afforded by the glass braid provided the fibres are dry, but at present there is no satisfactory way of impregnating the braid to prevent it absorbing moisture.

Pren is attacked by high-temperature-resisting lubricants of the ester-base type which are used in many gas-turbine engines. Protection against these lubricants has been obtained by extruding a thin Nylon sheath over the Pren. This is not entirely satisfactory for several reasons. Nylon is flammable; the sheath rucks when the cable is bent to a small radius and it detracts from the flexibility of the cable. There are difficulties, too, in manufacturing a uniformly thin sheath on the larger cables, and lacquered Nylon braid is used for cables of more than 24 amp rating. Unfortunately, braiding is a much slower process than extruding a sheath and therefore more costly.

For about ten years Pren has been the general-purpose cable for British aircraft but its position is being challenged by cables which are lighter by between 20 and 30 per cent in smaller sizes. These reintroduce poly-vinyl-chloride protected by glass braid and an extruded Nylon sheath. In the larger sizes, as for Nylon-protected Pren, lacquered Nylon braid is used instead of extruded Nylon sheath. The temperature range for this cable, called Nyvin, is the same as for Pren, −75 to +90 deg. C. Nyvin is superior to Pren in that it is resistant to ester-based lubricants and that it has a superior insulation resistance.

For operation at higher temperatures silicone rubber is used. This was

introduced some years ago in a British cable called Glasil in which the silicone rubber was protected by an external glass braid. Its temperature range was −75 to +150 deg. C. This cable is nearly 1½ times larger in diameter than Pren and is adversely affected by kerosene and lubricating oils. At the time of its introduction difficulty was being experienced with the use of external glass braid owing to the expansion of the insulating material and the inextensible nature of glass fibres. To avoid rupture of the braid, Glasil cables used a layer of felted asbestos between the silicone rubber and external braid. This difficulty has subsequently been overcome by refinements in the braiding technique.

Silicone rubber is now used in a light-weight cable known as Tersil. Asbestos is not used in this cable and a glass braid together with polyethylene-terephthalate, also known as Terylene, is used for the outer covering. These materials are rated to operate continuously within the temperature range −55 to +190 deg. C. and to withstand an 1,100 deg. C. flame for 5 minutes without electrical failure. This flame test gives an indication of the ability of the cable to continue operating in a burning aircraft. Like Nyvin, Tersil is lighter than Pren in small sizes.

An even higher operating temperature, 240 deg. C., is possible with poly-tetra-fluoro-ethylene (p.t.f.e.) insulation. This material has the additional advantage of being unaffected by all fluids used in present aircraft and it is non-combustible. It is extruded on to nickel-plated copper conductors and sintered with glass fibres. A final coat of p.t.f.e. enamel provides a low frictional surface to assist installation. These cables, known as Efglas, are heavier and larger in diameter than Pren except in the smallest sizes. Although the upper operating temperature of the insulation is higher than that of silicone rubber, p.t.f.e. cables cannot withstand the flame test.

Other special cables are used, such as fire-resisting cable for fire-detection circuits and high-temperature high-tension cables for engine ignition equipment. Fire-resisting cable is insulated principally with asbestos and glass. It will operate continuously at 240 deg. C. and will withstand 1,100 deg. C. for 5 minutes. Piston-engine ignition cables are interesting because the insulation is stressed by relatively high voltages, up to 15 kilovolts, and natural rubber is still used because it is one of the few materials having adequate dielectric strength at the temperatures existing in the proximity of engines, 120 to 140 deg. C. Gas-turbine ignition cables, suitable for up to 200 deg. C., are made with p.t.f.e. insulation, this being practicable because gas-turbine igniter circuits operate at lower voltages, about 2·5 kilovolts.

CABLE CONDUCTORS

Multi-strand tinned-copper conductors with strands of between 0·006 and 0·018 in. diameter are standard. These strand diameters are much smaller

than those commonly used for static wiring and give greater flexibility and reduce the risk of failure by fatigue. Aluminium is used in larger cables in strands of 0·020 in. diameter. Smaller strands are not used because they are difficult to draw and join. An aluminium conductor having the same resistance as a copper conductor, has only 2/3 of the weight but twice the cross-sectional area of the copper conductor. The larger cross-sectional area is a disadvantage not only because the cable is larger and less flexible but also because extra insulation is required to cover it. At present aluminium conductors are available with Pren and Nyvin insulations in nominal ratings of between 35 and 200 amp. These are known as Prenal and Nyvinal respectively and are about 2/3 of the weight of equivalent copper cables. The fact that aluminium cannot be soldered by the usual method has ceased to be very important since the adoption of crimped terminals, which are described later.

Nickel-plated copper strands are used in fire-resistant cables and in cables where operating temperatures exceeed about 160 deg. C., since at this temperature tin begins to alloy slowly with copper. The melting point of tin is only 232 deg. C., so high manufacturing temperatures, such as are necessary for extruded p.t.f.e. cables, also require nickel-plated strands. Stainless steel is used for piston-engine ignition cables where currents are very small and high mechanical strength is a primary requirement. Cadmium copper is also being introduced in small cables in which the strength of the conductor, in pure copper, is marginal.

CABLE RATINGS

The principal quantities which must be limited in operating a cable are the voltage and current. Aircraft power system voltages are all relatively low and any cable may be expected to be safe, even on the highest system voltage. This is because the thickness of insulation is determined, not by voltage, but by the requirement for a cable which can be installed, inspected and sometimes roughly treated, without suffering damage to its insulation. Owing to the flexibility of airframes, considerable movement occurs between the cables and the members to which they are attached, necessitating insulation capable of resisting wear and chafing. Ignition cables are among the few types in which insulation thickness is determined partly by voltage.

Current rating is determined primarily by the temperature of the insulation but this rating is frequently unusable because of excessive voltage drop along the cable. This is particularly true in a low-voltage system and where short-time cable ratings are being considered.

For a short time after a cable begins to carry current most of the heat developed in the conductor is absorbed by the conductor and the insulation. As the temperature of the cable is raised, an increasing amount of heat is

dissipated from the external surface and the cable temperature increases less rapidly. Finally a steady state is reached in which all the heat developed in the conductor is passed through the insulation to the external surface, where it is transferred to the atmosphere and adjacent solid bodies. In the steady state, the insulation material which is next to the conductor is at the highest temperature, the actual temperature depending on (*a*) the heat being developed in the conductor, (*b*) the thermal conductivity of the insulation, and (*c*) the ambient temperature and other external conditions such as the proximity of other cables.

British nominal current ratings are selected so that for cables in free air the maximum temperature of the insulation is 40 Centigrade degrees above the temperature of the air. This means that for p.t.f.e. insulation, which can operate at 260 deg. C., the maximum ambient temperature for a cable operating at the specified rating is 200 deg. C. If it is necessary to operate a cable in an ambient temperature, t deg. C., which is less than 40 Centigrade degrees below the maximum permissible temperature for the insulation, T deg. C., the specified current rating should be multiplied by $T-t/40$, which is always less than unity.

When cables are bunched together in looms or conduit, heat dissipation from the external surfaces is impaired and the cable ratings are reduced to avoid excessive insulation temperatures. Typical British ratings for Pren cable are given in Table 10.1. The nominal ratings are those by which British cables are designated and identified. They are approximately the ratings for cables in typical bunches; for example, it is expected that a number of small cables will usually be bunched together, so that the cable which is given a nominal rating of 4 amp. can be operated at 4 amp. in a bunch with 11 other cables of the same size, each carrying 4 amp. For larger cables, however, the nominal rating is applicable only to smaller bunches.

The method of cable designation used in the U.S.A., and now coming into use in Britain, is to allot to each conductor the American Wire Gauge (A.W.G.) number of a single strand having the nearest equivalent cross-sectional area. This designation is not related directly to current rating but, since the relationship between British nominal ratings and current ratings are not straightforward, it is to be expected that the U.S.A. designation may be generally adopted. The U.S.A. designations of the cables listed in Table 10.1 appear in the final column.

Short-time Ratings. Before a cable reaches its rated maximum temperature, heat may be developed at a greater rate than is possible continuously, without causing excessive insulation temperature. The time taken to reach the maximum permissible insulation temperature is decreased as the current loading is increased. From these facts it follows that short-time ratings of cables can sometimes be considerably higher than continuous ratings. Typical

Table 10.1

NOMINAL RATINGS OF CABLES

Nominal rating	*Number and diameter (in.) of strands*	*Nominal cross-sectional area (sq. in.)*	*Maximum continuous ratings in amperes for cables bunched in free air*				*Nearest A.W.G. number*
			Single cable	*3 cables*	*7 cables*	*12 cables*	
4	19/·006	0·00054	11	7	5	4	22
12	40/·0076	0·0017	21	15	11	7	16
35	73/·012	0·0082	61	47	36	25	10
135	203/·018	0·0525	200	155	120	—	2
280	666/·018	0·1700	350	270	200*	—	0000

* signifies approximate

Table 10.2

SHORT-TIME RATINGS OF CABLES

Nominal rating	*Maximum five-minute ratings in amperes for cables bunched in free air*			
	Single cable	*3 cables*	*7 cables*	*12 cables*
4	12	8	7	6
12	25	19	14	13
35	71	56	48	45
135	305	265	250	—
280	570	555	540*	—
Nominal rating	*Maximum one-minute ratings in amperes for cables bunched in free air*			
	Single cable	*3 cables*	*7 cables*	*12 cables*
4	15	12	9	9
12	33	28	26	25
35	110	107	104	101
135	545	530	520	—
280	1,255	1,240	1,210*	—

* signifies approximate

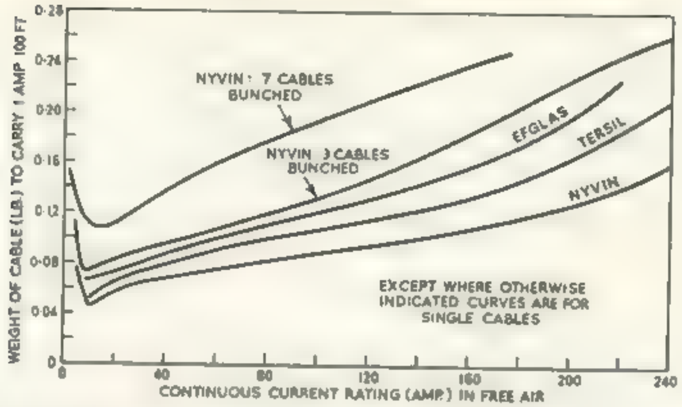


Fig. 10.1. *Curves relating specific weight and rating for various types of cables.*

short-time ratings are given in Table 10.2. Voltage drop increases in proportion to current and often prevents the use of these ratings.

Comparison of Current Densities. It is instructive to compare cables on a basis of pounds weight to carry one ampere 100 feet. This quantity will be referred to as the specific weight, and curves relating it to current rating are shown in Figs. 10.1 and 10.2. It can be seen from Fig. 10.1 that the Nyvin cable with the lowest specific weight is rated at between 5 and 15 amp., the exact value depending on the conditions of installation. Smaller cables have higher specific weights because they carry a large proportion of insulating material, and larger cables because they are operated at relatively low current densities. Fig. 10.3 shows how current densities decrease as cable size is increased, and Fig. 10.4 how the ratio of insulating material to copper increases as the cable size is reduced.

Lower current densities are necessary in larger cables because, if the

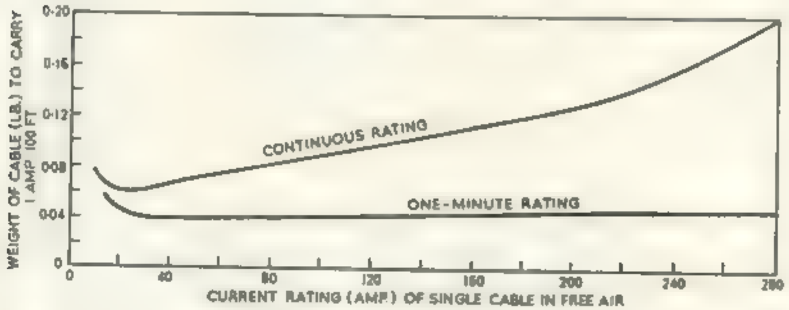
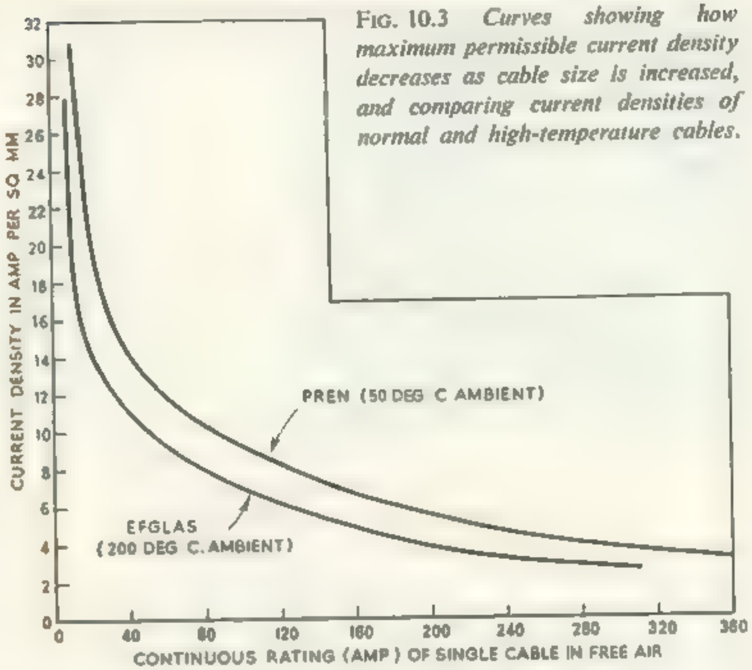


Fig. 10.2. *Curves relating specific weight with continuous and one-minute ratings of Pren cable.*

Fig. 10.3 *Curves showing how maximum permissible current density decreases as cable size is increased, and comparing current densities of normal and high-temperature cables.*



current density were the same for all sizes, larger cables would operate at higher temperatures. This arises because, with a fixed value for current density, the heat developed per unit length of cable is proportional to the volume, whereas heat dissipation is proportional to the surface area. Since volume is proportional to radius squared whereas surface area is proportional only to radius, it follows that, if the maximum permissible insulation

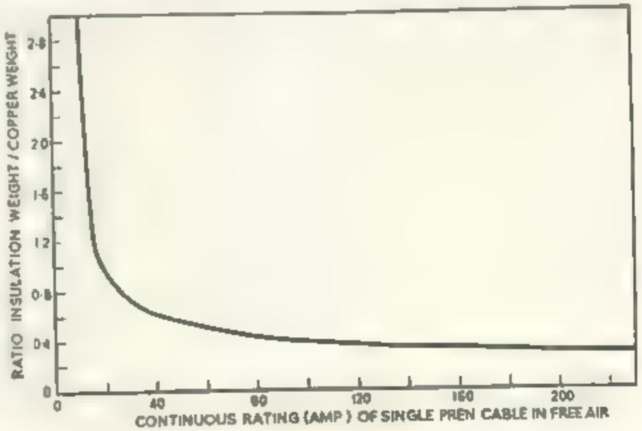


Fig. 10.4. *How the weight ratio of insulation to copper changes with cable size.*

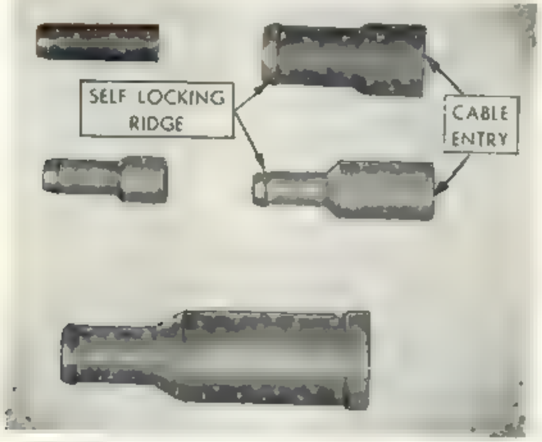


FIG. 10.5. *Aircraft cable ferrules for S.B.A.C.-type terminal block.*

temperature is not to be exceeded, the heat developed per unit volume of conductor must be decreased for larger sizes. This is done by decreasing the operating current density.

Short-time ratings do not depend very much on heat dissipation but mainly on the thermal capacity of the conductor and insulation. Because of this, it is found that they invoke similar current densities for all sizes of cable and specific weights, for short-time ratings, do not increase very much with cable size. This is indicated in Fig. 10.2.

From the fact that cables of a particular size, such as Pren with a maximum continuous rating of about 30 amp. (see Fig. 10.2), have the lowest specific weight it follows that five 30-amp. Pren cables are lighter than one 150-amp. cable. This is true, but the saving in cable weight is generally offset by the complexity and extra weight of cable fittings, terminals and protective equipment. The use of several cables in parallel has advantages for some methods of system protection which are discussed later (see *Main Feeders*).

High-temperature Cables. Since the resistance of copper increases with temperature, the rating of a high-temperature cable is lower than that of a cable for normal temperatures having the same conductor dimensions. This is necessary because increased cable resistance causes increases both in the heat developed and in the volt drop, and its effects

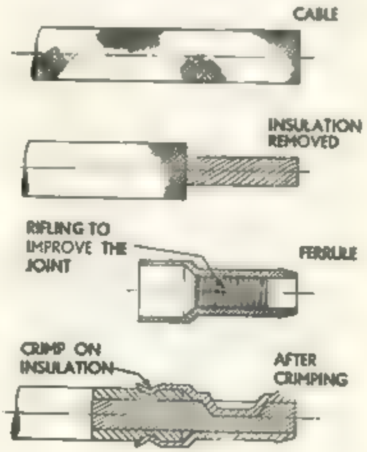
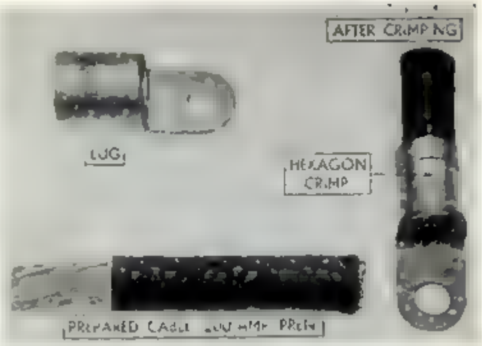


FIG. 10.6. *Stages in the fitting of a crimped-on cable ferrule.*

FIG. 10.7. *Cable (200-amp.) and crimped-on cable lug.*



can be offset only by working a cable at a lower current density. The resistance of copper increases by nearly ½ per cent per deg. C., so that cable resistance doubles with a temperature increase of just over 200 deg. (see Chapter 5, under *Cooling*). Fig. 10.3 compares the current densities permissible for Pren and Efglas under the same conditions except that the Efglas may be operated in an ambient temperature of 200 deg. C. whereas the Pren is limited to 50 deg. C.

CABLE TERMINATIONS

Considerable effort has been made in the last decade to improve the methods of terminating cables. It is accepted now that all cable ends are fitted with terminal lugs or ferrules and that the method of fixing is by crimping. This is a process in which an indentation or distortion of the terminal shank is used to secure the terminal to the conductor. Fig. 10.5 shows some typical silver-plated brass ferrules. Fig. 10.6 shows cross-sectional diagrams of a ferrule being crimped to a cable, the crimp being formed by a single indentation or dimple which distorts both ferrule shank and conductor. This type of ferrule, in common with most terminals used for cables of less than about 50 amp. rating, extends over, and is actually crimped on to, the cable insulation. This feature has been found to be necessary for small cables where the insulation contributes significantly to the mechanical strength of the cable, in order to prevent undue stress and flexure of the cable near the ferrule. Fig. 10.7 shows a crimped terminal on a 200-amp. Pren cable. In this case the crimp takes the form of a hexagonal compression of the shank and an exceptionally good joint is obtained. This type of crimp is sometimes referred to as a confined crimp and is probably preferable to a dimple crimp, which tends to disperse the conductor strands. The force required to make large crimps is sufficient to justify the use of powered crimping tools whereas the small crimps can be made with hand-operated tools, rather like pliers. Fig. 10.8 shows cross-sections of the conductors at the shanks of hexagon crimps. The distortion of the individual conductor strands, which were originally circular, is easily seen.

Crimping is superior to soldering in several ways. As a process it is more readily controlled and the results are more consistent; for example, there can

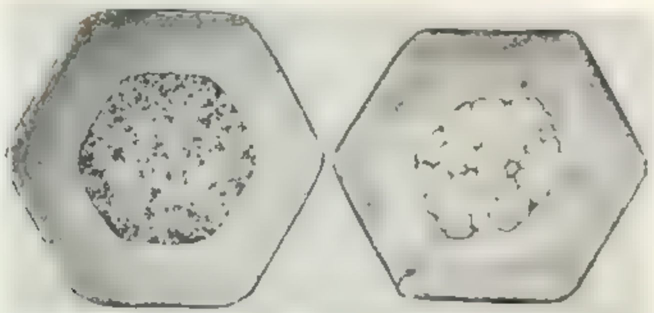


FIG. 10.8. (Left) *Cross-section of a 200-amp. cable with a hexagon crimped lug* (2 *magnification*). (Right) *Cross-section of a 50-amp. aluminium cable with a hexagon crimped lug, showing distortion of individual conductors* (5 *magnification*).

be no dry joints, excess flux or scorched insulation. The resistance between the cable conductor and terminal is lower, and more consistent values are obtained at crimped joints. The mechanical strength is greater, particularly at elevated temperatures. In tension it is found that the pull-off strength of crimped terminals is usually greater than the tensile strength of the cable. The behaviour of crimped terminals when operated continuously at a temperature above 100 deg. C., is at present suspect since it is believed that high-resistance joints can develop at the crimp. A refinement in crimped terminals is the use of a plastic sleeve bonded to the terminal shank, which is sufficiently tough to withstand the crimping forces. Examples of this may be seen in Fig. 10.9.

Crimping to aluminium conductors was, at first, unsatisfactory owing to the insulating film of aluminium oxide which is present on all strands, but it has been found that an oxide-removing paste can be used which, if

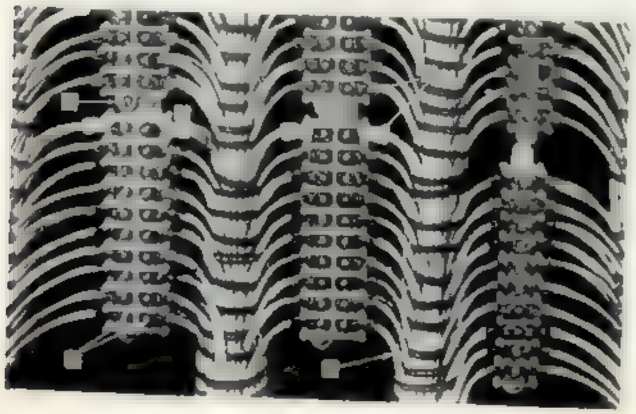


FIG. 10.9. *An installation using Vicker-strip terminal blocks, Nyvin cables and A.M.P. insulated, crimped, ring-type terminals:* A, *offset fixing lugs;* B, *ring-type terminals with insulated crimped sleeves;* C, *terminal identification;* D, *Nyvin cables;* E, *4 B.A. or 6-32 U.N.C. threads.*

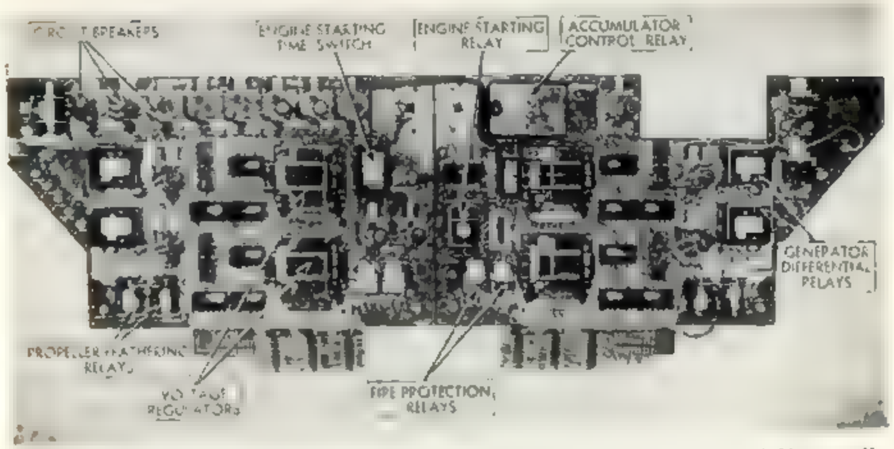


FIG. 10.10. *Main power system control panel fitted to an early Vickers "Viscount"*

applied to the conductor before crimping, renders the joint permanently satisfactory.

Cable lugs of the type shown in Fig. 10.7, which are of silver-plated brass, are also made in aluminium but particular attention is necessary to design and installation since, if a slightly high contact resistance is allowed to develop, the subsequent heating may worsen the contact resistance and ultimately cause the lug to melt. The melting point of aluminium is only 660 deg. C. whereas brass melts at between 800 and 1,000 deg. C. and copper at 1,083 deg. C. Brass has been criticized as a material for lugs which are formed by cold working because it is liable to season cracking.

SOLID CONDUCTORS

Solid conductor, instead of multi-strand cable, is used in a few parts of aircraft installations for one or more of the following reasons: (*a*) solid conductor requires less elaborate supporting arrangements; (*b*) it can be shaped precisely, and to follow much smaller radii, than cable; (*c*) adequate insulation can be lighter than standard cable insulation; (*d*) round, rectangular and other cross-sections can be used.

It is usual to find solid strip conductors used as busbars and for interconnecting heavy-current components mounted close together. An example of the latter application can be seen in Fig. 9.11. The connexion of suitably terminated cables to strip is simple and the strip itself can easily be fitted with terminal studs thereby minimizing the number of fittings required for an installation. Both aluminium and copper have been used for busbars and, although some difficulties have been experienced with aluminium on account of its oxide film, low yield strength and high coefficient of expansion, it is

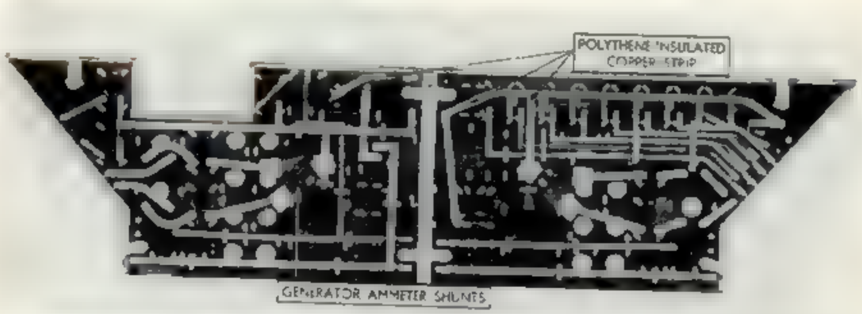


FIG. 10.11. *Rear view of the control panel, showing the heavy-current connexions.*

satisfactorily used on present day British aircraft. To avoid the oxide film difficulties, copper-plated and copper-clad aluminium are proposed as alternative light-weight materials. Fig. 10.10 shows the front and Fig. 10.11 the rear view of the main power panel of an early Vickers "Viscount" built for Air France. It uses copper strip insulated with polythene for the heavy current connexions.

CONNECTORS

All devices for connecting two or more cables, or for connecting cables to equipment, are included under this heading. These are principally terminal blocks, and plugs and sockets. Probably the only fundamental electrical requirement of a connector is low contact resistance, but specifications for connectors are frequently elaborate because connectors have so often failed to provide this simple feature or have been the location of other faults.

Terminal Blocks. A commonly used British terminal block, sponsored by the Society of British Aircraft Constructors (S.B A.C.), is shown in Fig. 10.12. These blocks are designed to receive the cable ferrules shown in Fig. 10.5 and the mechanism by which ferrules are secured is shown in Fig. 10.13. When the terminal locking screw is slack the ferrule may be inserted or withdrawn from the split socket clamp, but the contact pressure spring applies sufficient force to ensure that the annular ridge at the ferrule tip prevents the ferrule from falling out or being accidentally withdrawn. On tightening

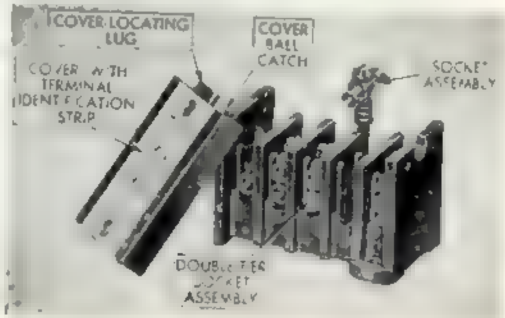
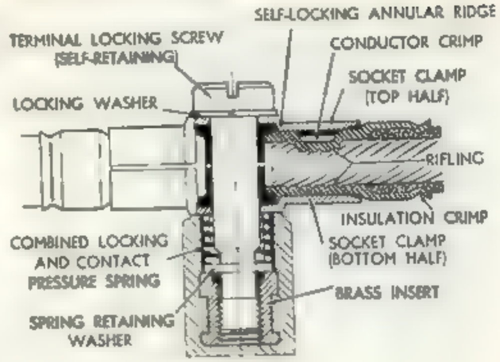


FIG. 10.12. *S.B.A.C. terminal block rated at 19 amperes.*

FIG. 10.13. *Sectional diagram of S.B.A.C. terminal block socket assembly.*



the locking screw, the split socket is solidly clamped against the moulded base. This type of block is made in two sizes rated at 19 and 37 amp., both sizes being suitable for all aircraft power system voltages.

A terminal block for smaller currents was initiated by A.V. Roe & Co. Ltd., about 1950, and is now available rated for currents up to 12 amp. An exploded view of the block is shown in Fig. 10.14. Unlike the S.B.A.C. block it uses sockets which are not rigidly secured to the base and which are formed from single pieces of silver-plated beryllium copper. The sockets are shaped so that each cable ferrule makes line contacts with the sockets, which are wiped as the ferrule is inserted. Socket dimensions ensure that the cable ferrules fit tightly, giving good contact and retention of cable ferrules during assembly. Withdrawal of ferrules is prevented after the sockets have been inserted between the walls of the block by projections at the ends of the walls. Sockets are retained in position between the walls by projections on the under side of the cover.

The double and single sockets permit the interconnexion of six and three cables respectively, all of which may enter the block from either side. The block design incorporates many detail refinements, such as the provision of

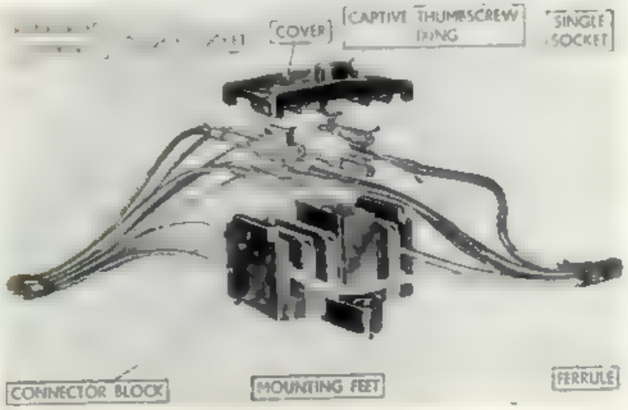


FIG. 10.14. *Exploded view of Avro light-weight terminal block.*

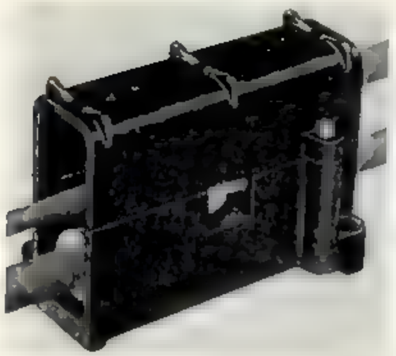


FIG. 10.15. *Avro heavy-duty single-way terminal block.*

clearance between the base of the block and the panel on which it is mounted in order to minimize the accumulation of moisture. The possibility of accidental earths has been minimized by ensuring that no live metal is exposed and that fixing screws, which may be expected to be earthed, are unlikely to make accidental contact with live metal. Identification markings are provided on the cover, which can only be fitted on in one way.

Heavy-current terminal blocks are available both in S.B.A.C. and Avro ranges. Figs. 10.15 and 10.16 show an Avro block which can accommodate two lugs each side, of up to 230 amp. rating. Gaps in the side walls of the base allow commoning strips to be fitted between adjacent blocks.

A recent attempt to reduce the weight of low-current terminal blocks has resulted in the Vickerstrip terminal block system. These blocks are a return to the simple form, of studs carried in a moulded base. Examples of single and double blocks may be seen in Fig. 10.9. The studs are threaded 4 or 6 B.A., or the equivalent unified threads, and are moulded in to a non-rigid Nylon base. They are separated by barriers which have enlarged ends to prevent short-circuiting between the terminal sleeves. Although the barriers are very thin, the superior mechanical properties of Nylon are an adequate safeguard against

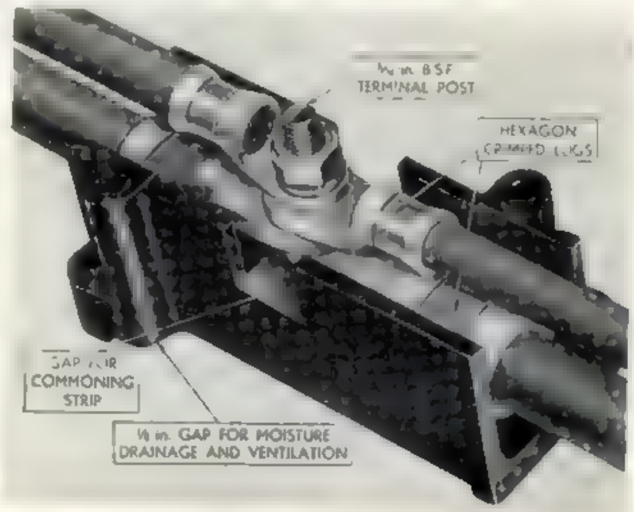


FIG. 10.16. *Avro heavy-duty single-way terminal block with cover removed.*

accidental breakage. The studs, which are made of an electro-tinned silicon nickel-copper alloy, are long enough to accommodate four ring-type terminals suitable for Pren cables of 4-amp. nominal rating, or two terminals for cables of 35-amp. rating. The weight of a 10-way double block having 4 B.A. studs is only 0·183 lb.

MULTI-PIN PLUG AND SOCKET CONNECTORS

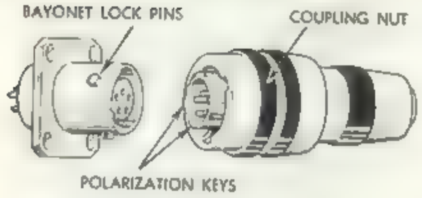
These components are invaluable but are penalized by an element of unreliability which, although small, cannot be disregarded. In fact it is accepted by some British authorities that there are certain vital aircraft circuits from which plug and socket connectors must be excluded.

The principal reasons for using plugs and sockets are: (*a*) to provide a means of quickly disconnecting and reconnecting a large number of conductors; (*b*) to ensure the correct order of connexion; and (*c*) to provide a large number of connexions in a small space. Equipment which is removed from aircraft for repair or servicing is often connected by plugs and sockets for reasons (*a*) and (*b*). At engine bulkheads and wing roots economy of space is frequently an important consideration.

The kinds of failures which occur in plug and socket connectors are: (*a*) fracture of the conductors near the pin and socket contacts; (*b*) displacement or distortion of pin and socket contacts; and (*c*) tracking causing a low-resistance path between contact pins. This is usually the result of water entering the connector and causing corrosion.

Remedies have been offered for each of these kinds of failure but none has proved to be complete for all circumstances and types of connector. The possibility of fracture of the wire behind pin or socket contacts is greatly decreased if the cable entering the connector is not moved or flexed during operation or when the connection is made or broken. Complete freedom from movement at the cable entry can be achieved only when the plug and socket are built into the equipment and the equipment racks. Plug-in equipment gives rise to additional problems, such as ensuring correct alignment, complete mating and freedom from fretting at the contacts. Flying connectors are indispensible at such places as fireproof bulkheads. Potting, or filling, the cavity behind the pin and socket contacts with a rubber-like material is helpful in relieving stresses and flexure of the wires, but is not always acceptable because connexions to a potted connector are not easily modified. The details of cable preparation, and crimping or soldering to the contact, also affect the life of the wire. Consistent workmanship here, probably calls for more rigorous inspection than is generally attainable.

Distortion or displacement of plug or socket contacts often arises from attempts to mate the plug and socket while they are misaligned. Even the highest intentions are insufficient to ensure that this is never done, and when



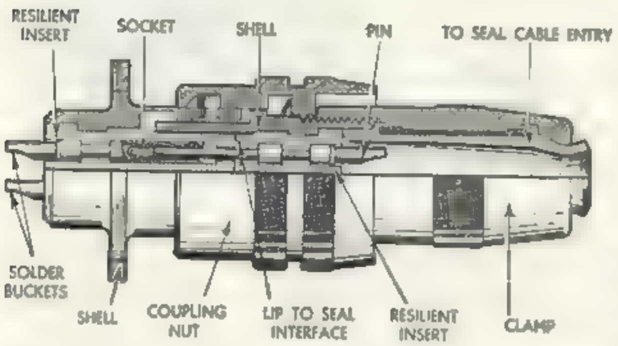


FIG. 10.17. *Outside and sectional views of a Bendix Pygmy plug and socket connector.*

it has been done the damage may be practically undetectable. Again, partial remedies are available in the forms of aligning spigots, closed-entry sockets and resiliently mounted pins, but none of these gives complete protection. The connector shown in Fig. 10.17 has resilient pin inserts, and the metal shells of the connector shown in Fig. 10.19 are designed to ensure alignment before the pins are entered into their sockets. A closed-entry socket is one on which the periphery of the socket orifice is continuous.

The exclusion of water from a plug and socket connector is a task of some difficulty. Sealing is required at the following places: (*a*) the interface between the mated components; (*b*) the cable entries; (*c*) the pin and socket contact inserts, to avoid the ingress of moisture while the plug and socket are separated.

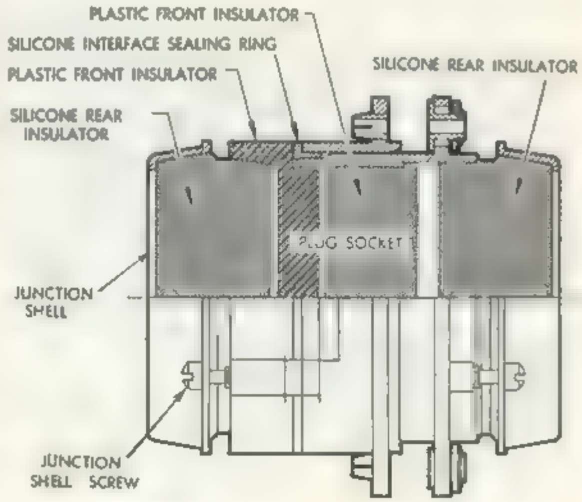


FIG. 10.18. *Sealing arrangements of a Cannon plug and socket connector. Contact cavities in the insulators are not shown.*

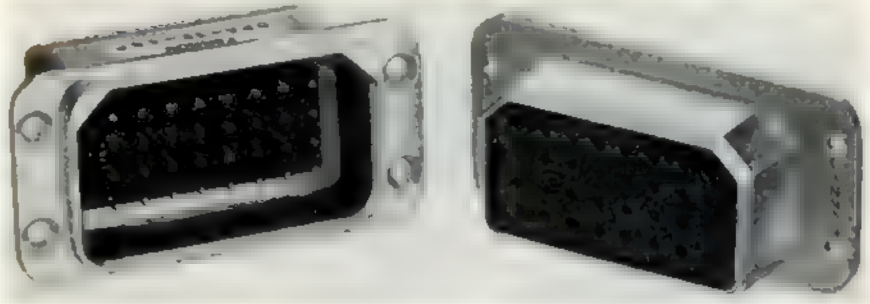


FIG. 10.19. *Cannon plug and socket connector having die-cast aluminium-alloy shells which align the contacts before entry. Weight of the pair, 0·12 lb.*

Sealing may also be required at the mounting flange of connectors fitted to sealed equipment. Few plug and socket connectors are marketed with complete sealing and those which are available are larger, heavier and more difficult to assemble than unsealed types. Fig. 10.18 shows the sealing arrangements of a Cannon plug and socket of a similar type to the one shown in Fig. 10.19. These include a silicone rubber sealing ring for the interface seal and monobloc silicone rubber inserts, which are compressed by the tightening of the junction shells, to seal around the wires near the cable entries. The rectangular shape of these connectors sometimes enables a higher utilization to be made of panel or bulkhead area.

The passage of cables through bulkheads is often broken by plugs and sockets because the bulkhead is either fire-resisting or forming a wall of a pressurized zone. Fig. 10.20 shows a double-sided plug for a pressure bulkhead which has pins of two different current ratings. The different diameters are clearly seen. This is an invaluable feature for accommodating circuits of different power ratings. Double-sided terminal blocks have also been used at bulkheads but these require more space than plug and socket connectors and are now only used for very heavy currents.

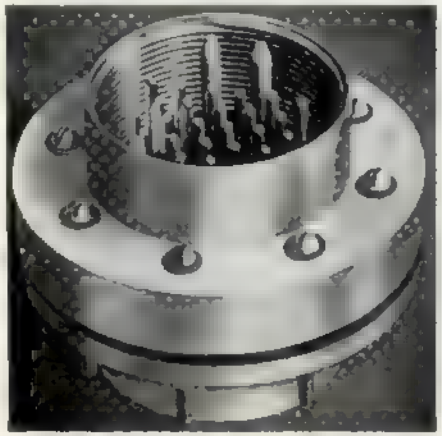


FIG. 10.20. *Breeze pressure-proof bulkhead plug. Overall diameter 2·7 in. Weight, 6 oz. It has two large pins (19-amp.) and 24 small pins (7-amp.).*

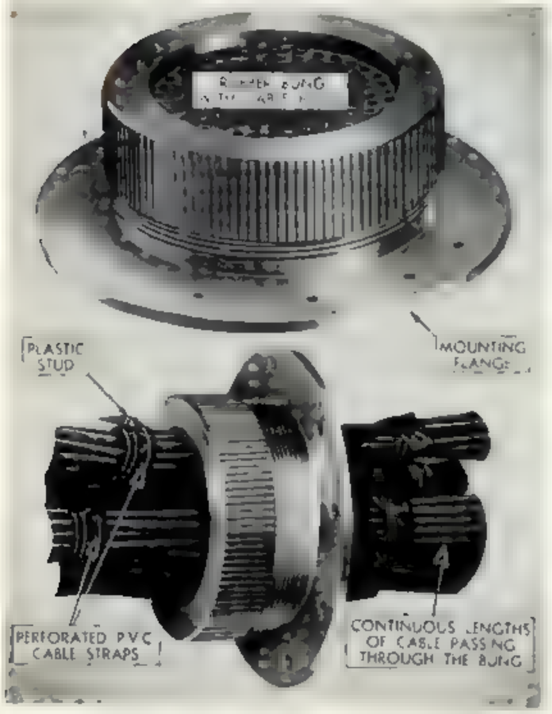


FIG. 10.21. *Helvin pressure-tight bung and p.v.c. cable strap.*

An alternative fitting for pressure bulkheads is the rubber bung shown in Fig. 10.21. This simple component avoids the problems associated with plug and socket connectors since the cable is passed through the bung without being cut. It is also much lighter than a connector. Holes in the bung are closed by a thin rubber diaphragm at one end which is pierced to allow the cable to be fitted.

CONDUIT, TRUNKING AND CABLE FITTINGS

Since aircraft power systems are wired principally with single-core cable it is necessary to provide means of keeping the cables together and out of positions where they are likely to be damaged. It is also desirable that they should be accessible for modifications and that it should be easy to add extra cables. The earliest method was to form looms, or bundles, of cables, binding them with waxed string at every few inches. Nylon cord, covered with a plastics material, is often used now instead of string. Looming is an acceptable method but it is troublesome to add or remove cables from a loom. An alternative to cord, which is popular with most British aircraft manufacturers is p.v.c. strap. This is supplied in reels and cut in lengths to suit the looms. The strap, shown in Fig. 10.21 is joined by plastic studs, rather like collar studs. It is obtainable in several sizes, and provided it is not overstressed it can be used satisfactorily several times.

Conduits are used in several forms. Plastic sheaths are lightweight, flexible and give some protection against liquids, but modifications are not easily made. Flexible metal conduits provide better mechanical protection and may also serve as electrostatic screening. Short lengths of rigid metal

conduit are occasionally used to convey cables from one section of an aircraft to another. Metal is superior to other conduit materials in preventing the spread of fire. A type of trunking which was used in the early "Comets" is shown in Fig. 10.22. The base of this trunking is fixed to the aircraft structure and the top can be removed so that lengths of cable can be lifted out or laid in. It is sufficiently flexible to allow twisting to suit aircraft contours.

BONDING AND EARTHING

Metal parts of aircraft are all electrically connected together, or bonded, primarily to ensure that all parts of the aircraft are at about the same potential. The most dangerous potential differences are likely to occur in the event of a lightning strike and the magnitude of the current surge expected from a major strike determines the necessary current-carrying capacity of "primary" bonding conductors. These are defined by the Air Registration Board (A.R.B.) (see Ref. 13) as conductors between major components, external metal surfaces and the main earth system, and are specified as having an equivalent cross-sectional area of not less than 0·009 sq. in. of copper. Lightning surge currents are estimated at as much as 50,000 amp. and are likely to cause fire, structural damage and electric shock if the bonding is of high resistance or burns out during the surge. With correct bonding, although the flash and bang which accompany major strikes may be frightening, the worst damage likely to be incurred is the burning of a small hole in the aircraft skin at the point of strike.

In "all metal" aircraft, many parts are adequately connected together and do not require bonding conductors, but in aircraft of non-metallic construction a "main earth system" is required. This should consist of strip copper of about 0·02 in. thick and 0·5 in. wide extending the whole length of the fuselage and from wing roots to tips. The number of strips is chosen so that the spacing does not exceed about 6 ft., measured round the aircraft fuselage or wings, and all are connected by lightning strike plates which are fitted at the extremities such as nose and tail.

Another source of potential difference is static charges which are frequently acquired by aircraft in flight as described in the following paragraph. These charges can cause shock and represent a fire risk, but are not of the same order of magnitude as those which cause lightning strikes.

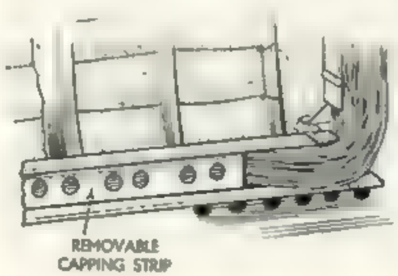


FIG. *10.22. Trunking of 0·03 resinated asbestos, with removable capping strip.*

Consequently the discharge currents are smaller, and smaller bonding conductors may be used. A further reason for bonding parts liable to accumulate static charges is to avoid the radio interference which occurs when such charges are allowed to discharge by corona effect or by sparking to adjacent metal parts.

Static charges are acquired on aircraft by two processes which are basically different. Charges are picked up by flight through snow, and to a lesser extent, rain. This is termed autogenous charging. They are also picked up by induction when an aircraft passes through or near to thunderstorm clouds, which are always charged. This is called exogenous charging. Exhaust gases leaving an aircraft also cause the build-up of a static charge but this is usually relatively insignificant. All charging processes cause a change of potential of an aircraft with respect to the surrounding atmosphere and, when this reaches about 200,000 volts, corona discharges occur from sharp edges and points on the aircraft surface. These discharges tend to be oscillatory or impulsive and may render all radio equipment inoperative while they persist. Autogenous charging is most serious because it is occasionally sustained for long periods during flight, whereas exogenous charging is usually intermittent.

Bonding prevents discharges between parts of an aircraft which, if separate, would probably acquire different potentials; but it cannot prevent discharges from an aircraft as a whole. While an aircraft is acquiring a charge, as in autogenous charging, it must simultaneously be discharged or its potential will rise until discharges occur by sparking instead of by corona. It is therefore desirable to facilitate corona discharge, if possible in a non-oscillatory form, in order to minimize radio interference. This is done by fitting corona discharge wicks; these are made from a textile wick impregnated with a substance such as colloidal graphite to render it partially conducting, and frayed at the free ends. The resistive nature of the wick tends to suppress the oscillatory nature of the discharge and the strand ends provide a large number of points which facilitate discharge.

Some static charge is liable to be present on an aircraft after landing and causes a difference in potential between the aircraft and the earth. To ensure that this charge is removed soon after a touch-down, since it might otherwise cause shocks to be experienced by alighting passengers or sparks between the aircraft and refuelling equipment, aircraft tyres are made of rubber having relatively low electrical resistivity. The A.R.B. specify that the resistance between the airframe and earth shall not be greater than 10 megohms. As a further precaution, aircraft fuel-filling points are provided with a means of bonding to the refuelling equipment. It will be appreciated that an aircraft bonded to give safety from lightning and static charges is almost ideally suited to function as a return or earth conductor for d.c. electrical power systems.

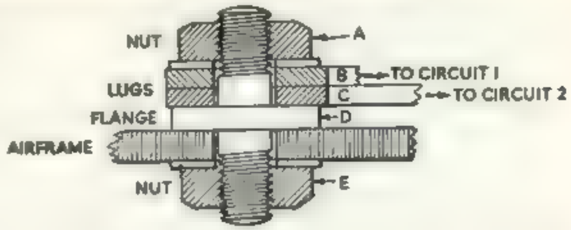


FIG. 10.23. *Sectional diagram of an earthing terminal.*

Earth Terminals. Points at which electrical equipment may be connected to the airframe are usually limited in number and are chosen and designed with some care. Many corrosion-resistant surfaces, such as anodized aluminium are good insulators and contact cannot be made to the metal unless the surface has been removed. This is generally fairly easily done by abrasion, chemical means or even by the forming of rivet heads, but locally the resistant surface is impaired and a protective paint or grease is usually applied. Magnesium and its alloys are particularly liable to electrolytic corrosion and are often protected with insulating surface finishes.

Consideration of a terminal, such as the one illustrated in Fig. 10.23 shows that electrical failure of an earth terminal can occur in several ways. There may be poor contact between lug *B* or lug *C* and the airframe. This can be caused by nut *A* being loose, by an improperly prepared airframe surface under flange *D*, or by corrosion at any of the adjacent surfaces. Looseness of nut *A*, even if it is initially tight and securely locked, may be brought about by settling of the surfaces under pressure. This will be accelerated by heating, particularly if the coefficients of expansion of the components are different or some of the materials are soft, and will be more serious if several lugs are fitted to the single stud. Since the currents carried by earthing studs are generally high and carried continuously, a very low resistance connexion is essential if heating is to be avoided.

If nut *E* is loose a poor contact may be expected between the terminal post and the airframe and a high resistance will be present common to both circuits 1 and 2. Thus, fluctuations of current in one of the circuits will cause voltage fluctuations in the other. The magnitude of these voltage fluctuations depends on the value of the resistance and the magnitude of the current fluctuations, and the consequences depend on the sensitivity of the equipment in the affected circuit. A very bad contact causing a high value of resistance may practically isolate the two circuits from earth although they would still be connected together. This condition is dangerous if circuits 1 and 2 are powered from supplies at different voltages; Fig. 10.24 (*a*) depicts an example in which a 28-volt load would experience nearly 70 volts. This fault could also occur if the structural member on which the terminal is mounted is not properly bonded to the main earth system of the aircraft, and

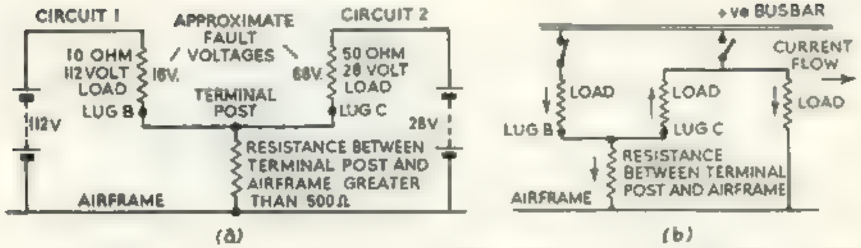


FIG. 10.24. (a) *Circuit depicting a fault condition which can arise at a faulty earthing terminal.* (b) *Illustrating the effect of an earth terminal fault.*

it is good practice to make the earthing arrangements of circuits supplied from systems of different voltages as independent as possible. Even when the two circuits are powered from the same supply it is still possible to experience trouble. Fig. 10.24 (*b*) illustrates a case where the operation of one load causes current to flow through the others.

For such reasons some aircraft constructors are adopting a double-studding technique. This is the provision of two studs where formerly one was considered sufficient. An example of this may be seen at a terminal of the transformer shown in Fig. 8.12.

CONTROL AND PROTECTIVE EQUIPMENT

Some definitions and discussion of the terms used for the equipment will probably help the understanding of the subject. These definitions are believed to conform with the present usage of most aircraft electrical engineers but do not exactly coincide with those recommended by the British Standards Institution.

Electrical Relay. A component, sensitive to electrical changes at low power level and capable of controlling one or more circuits, generally at a higher power level.

Switch. A non-automatic mechanical device for making and breaking a circuit carrying normal current.

Contactor. A switch adapted for remote operation.

Circuit-breaker. A device for making and breaking a circuit, both under normal and fault conditions.

Electrical Relays. Relays consist of one element which senses electrical changes and operates the relay mechanism, and another which controls changes. The sensing and operating element is a solenoid and the controlling element is one or more pairs of contacts. In many aircraft applications the solenoid is energized directly from the aircraft power supply and, for these cases, neither the power absorbed by the solenoid nor the "pull-in" or "drop-out" voltages are very critical. In other applications the solenoid may

be energized from an automatic device, such as a cabin temperature-control amplifier or an ice-warning detector circuit, and in such cases the amount of power available is limited. The voltages at which the relay pulls in or drops out are also likely to be critical. These two types of relays will be referred to as non-critical and critical respectively. Non-critical relays are often used as remotely controlled switches and in aircraft it is common to find such relays having contacts to carry up to 20 amp. and, occasionally, much higher ratings are used. No satisfactory distinction can be made between these relays and contactors.

Owing to the relatively limited power available to operate critical relays some types have very small operating and returning forces. Thus contact pressures are low and the forces available to separate the contacts are also small. Such relays are inherently sensitive to vibration and shock and are also liable to stick. The tendency to contact sticking or welding is increased if the contacts are operated at excessive current or under conditions which cause arcing. Critical relays are therefore rarely used to control more than a current of 1 amp. A very sensitive critical relay, called by its manufacturers a micropositioner, is shown in Fig. 10.25. It may be operated with as little as 40 microwatts and the tolerance on pull-in voltage is ± 25 per cent at 75 deg. C. Typical relays operate at about 100 milli-watts and have closer tolerances on pull-in and drop-out voltages. The effects of shock and vibration are minimized by using light-weight balanced armatures. Permanent magnets are employed to obtain maximum sensitivity and to make the relay sensitive to the polarity of the operating current.

The name *relay* is commonly extended to non-electrically operated devices such as the thermal relay which is used extensively to sense excess currents. They are also used to protect equipment such as motors and accumulators against overheating. The operating element of most thermal relays is a bimetal strip which distorts, and is capable of exerting a useful force, when subjected to a temperature change. The controlling element may be a pair of contacts operated directly by the bimetal strip, but for breaking excess

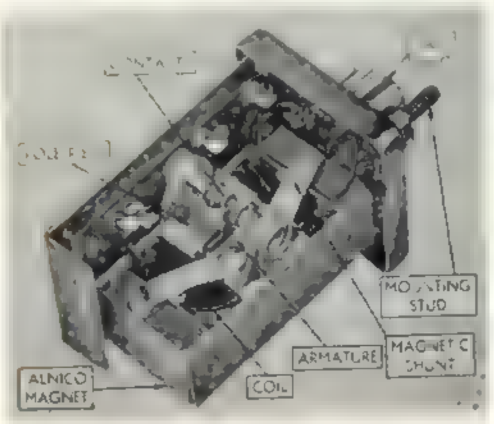


FIG. 10.25. *A sensitive critical relay assembled on a plug-in base. The unit is hermetically sealed and weighs 0·53 lb.*

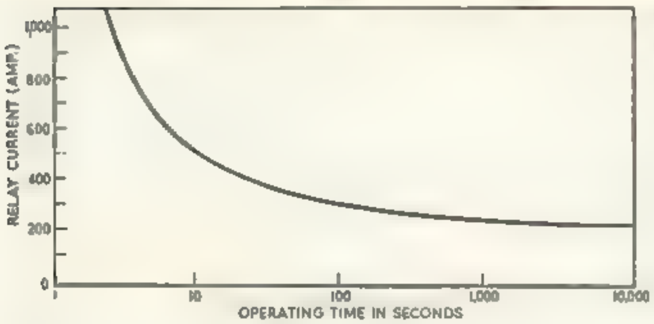


FIG. 10.26. *Operating characteristic of a thermal relay fitted to a 200-amp. circuit-breaker.*

currents it is usual for the device to operate the trip mechanism of a circuit-breaker. Limitations of thermal relays are that they are inherently insensitive to current direction and sensitive to ambient temperature. A characteristic of their performance when operated as excess-current relays is that the time of operation is approximately inversely proportional to the current. This is indicated in Fig. 10.26. Other non-electrical relays are operated by such quantities as oil pressure, and air pressure arising from forward air speed, but these are more generally known as pressure sensing switches. Relays adapted for specific purposes such as over-voltage relays, and differential current relays are discussed in the Sections dealing with their applications.

Switches. The most common type of switch is the manually operated tumbler switch which is generally available in ratings up to about 20 amp. Higher ratings are required for special purposes, notably Ground/Flight switches which transfer an entire aircraft d.c. power system from the aircraft battery to a ground supply. Push-button switches are used for a variety of purposes such as undercarriage and bomb-bay door operation. Micro-switches, switches operated by a small movement of a plunger or lever, are used to indicate positions of mechanisms and for interlock circuits.

In addition to the switches mentioned, all of which are fairly standard components, there are a number of special switches used in aircraft, such as the aileron, elevator and rudder trim switch, shown in Fig. 10.27. This switch is operated by pushing the knob to the left or right to switch on the aileron trim actuators, up or down to switch on

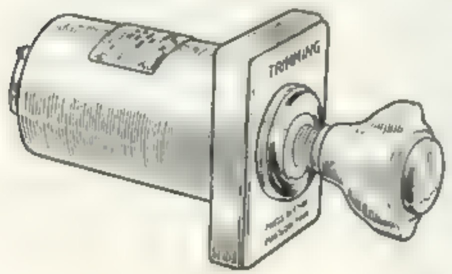
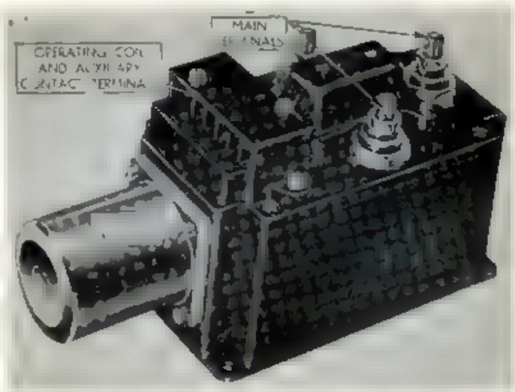


FIG. 10.27. *Multi-position switch for controlling aircraft trim actuators. Weight: 1·8 lb.*

FIG. 10.28. *Single-pole change-over contactor rated to switch 30 amp. at 112 volts, at an altitude of 60,000 ft. Weight: 5·5 lb.*



the elevator trim actuators, and turning the knob to switch on the rudder trim actuator. One further facility, built-in to this switch, is the centre push-button for selecting high- or low-speed actuator operation.

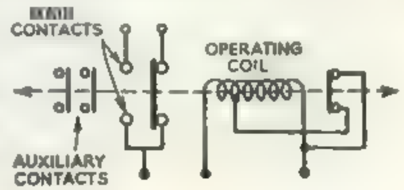
Contactors. The contactors used in aircraft are nearly all electrically operated. In many types the operating coil remains energized at a reduced current value while the contactor is closed, but contactors which are intended to remain closed for long periods of time generally have latching mechanisms. Latching mechanisms are also fitted to most circuit-breakers and are described in the next Section. Operating solenoids are almost invariably energized from a 28-volt d.c. supply. This low voltage minimizes arcing at the contacts of the switch or relay controlling the solenoid and avoids the use of very fine wires which are necessary for small high-voltage solenoids. Direct current is preferred to a.c. for the reasons discussed in the Section on Solenoids (see Chapter 9).

A recently developed a.c. industrial contactor employs a permanent magnet for latching-in, the magnet being magnetized by an impulse at switching on, and demagnetized by alternating current on switching off.

A single-pole change-over contactor is shown in Fig. 10.28 together with its internal wiring diagram (Fig. 10.29) which shows how the coil current is reduced after the contactor has closed. The total resistance of the solenoid coil is 57 ohms, and of that part of the coil used for initial operation only 8 ohms. Thus the current and heat dissipation are reduced to about one-seventh of the initial value.

Circuit-breakers. Unlike any of the components previously discussed,

FIG. 10.29. *Internal wiring diagram for single-pole change-over contactor. The contact at the extreme right short-circuits part of the operating coil when the contactor closes.*



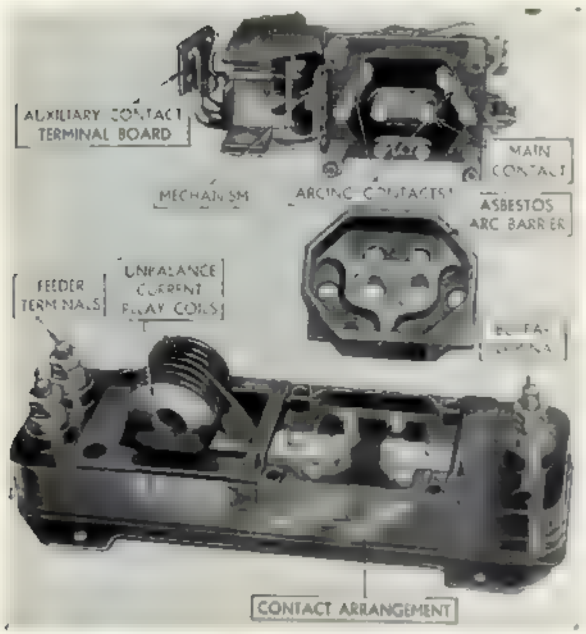


FIG. 10.30. *Dismantled view of one of the largest aircraft circuit-breakers. It is rated to carry 400 amp. and to rupture 8,000 amp. at 12,000 ft.*

circuit-breakers are specially designed to make and break circuits carrying fault currents. The low atmospheric pressure at altitude is unfavourable for breaking large currents in 112-volt d.c. circuits although it does not greatly affect the breaking of small currents. Currents in 28-volt d.c. and 400 c/s a.c. circuits are relatively easily broken.

Methods used for breaking large currents in 112-volt d.c. circuits often employ the principle of separating the arc into a number of short lengths. This is effective because a certain minimum voltage is necessary to maintain an arc, and at altitude this is almost independent of arc length. For typical conditions it is between 20 and 30 volts. Thus an arc separated into ten short lengths cannot be maintained by less than 200 to 300 volts. Separation of the arc is achieved either by using a number of pairs of contacts in series or by forcing the arc to play on a non-conducting grid called a deion grid. Fig. 10.30 shows a circuit-breaker using six pairs of contacts in series and Fig. 10.31 shows another which uses two pairs in series together with deion grids.

Other methods of arc extinction used in aircraft include magnetic blow-outs and materials which when heated evolve arc-quenching gas into the arcing chamber. The use of magnetic blow-outs is suspect because it has been reported that at high altitude the magnetic field may be ineffective. Also, when the magnetic field is established by the fault current its strength and effectiveness are dependent on the nature of the fault. Permanent magnets are used but are suitable only for unidirectional current flow.

Some circuit-breakers are closed electrically like contactors but others, particularly the smaller ones, are closed manually. Manual closing enables

high contact pressures to be achieved without the encumbrance of a large operating solenoid. Most types are held closed by a latch mechanism which may be tripped manually or magnetically with a small built-in solenoid. They may also be tripped by relay, such as a thermal relay sensitive to excess current.

The circuit-breaker shown in Fig. 10.31 has its two pairs of contacts arranged so that, if either pair should weld or stick, the other is free to open. It is closed by a built-in solenoid and remains latched-in. It has magnetic and manual tripping and also has a thermal bimetal relay which trips the latch mechanism in the event of an overload. Two pairs of 5-amp. auxiliary contacts are built-in, one pair being normally closed and the other normally open. The main contacts have a continuous rating of 80 amp. at 112 volts. The circuit-breaker weighs 5 lb.

Fig. 10.30 shows a circuit-breaker which has a continuous rating of 400 amp. at 112 volts and a breaking capacity of 6,500 amp. at altitudes up to 60,000 ft. and 8,000 amp. up to 12,000 ft. It is manually closed and remains latched-in, and can be tripped manually or magnetically. This particular circuit-breaker has a built-in unbalance current relay which trips the mechanism in the event of excessive unbalance. An application for this is described later (*see Main Feeders*). The main contacts, of which there are two pairs, are of silver-graphite, and the six pairs of arcing contacts are of silver-tungsten. The arcing contacts are arranged to close the circuit before the main contacts are closed, and to open it before they are opened. With this arrangement the main contacts are protected from arcing and can be designed primarily for low contact resistance. The circuit-breaker weighs about 7 lb.

A feature, now generally required, is that circuit-breakers are "trip free" so that they cannot be held closed while a fault is present. For some years this feature

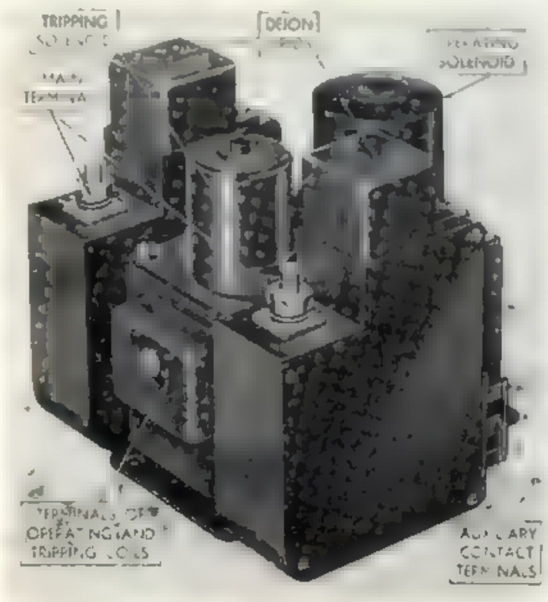


FIG. 10.31. *Single-pole circuit-breaker having a continuous rating of 80 amp. at 112 volts d.c.*

was the subject of controversy, as some authorities thought it advantageous to be able to hold the breaker closed while short-circuit faults existed, in order to burn the fault clear. The dangers of fire and structural damage have, however, increased with system capacity and non-trip-free circuit-breakers which allow this practice are no longer favoured. The possibility of keeping a vital circuit in operation, even though a fault is present which overloads the circuit-breaker, is comforting to the aircrew but it is not at all certain that this can generally be done; nor is it certain that the arcing which occurs at a short-circuit fault will usually burn away the contacting metals and leave the fault open. The only certain justification for non-trip-free circuit-breakers is that false operation of the breaker can be manually overridden.

Characteristics of circuit-breakers which are important under fault conditions are the fault-clearing capacity and the operating time. The former is generally quoted in amperes for aircraft circuit-breakers, a typical value for a large breaker being 5,000 amp. It is understood that currents of this magnitude, generally called major fault currents, may cause some damage to the contacts and that replacement of the contacts may be necessary after only a few operations on such faults. The operating time of a circuit-breaker may be subdivided into the time delay between energizing the circuit-breaker tripping device and separating the contacts, and the time taken to extinguish the arc. Contact separating time may be as little as 4 milli-seconds for a fast circuit-breaker and 7 milli-seconds is a typical time. Arcing time depends on altitude and current and lies between 6 and 12 milli-seconds in d.c. circuits. In a.c. circuits arcing time is likely to be less than the time between current zeros, which is half a period or $1\frac{1}{4}$ milli-seconds at 400 c/s.

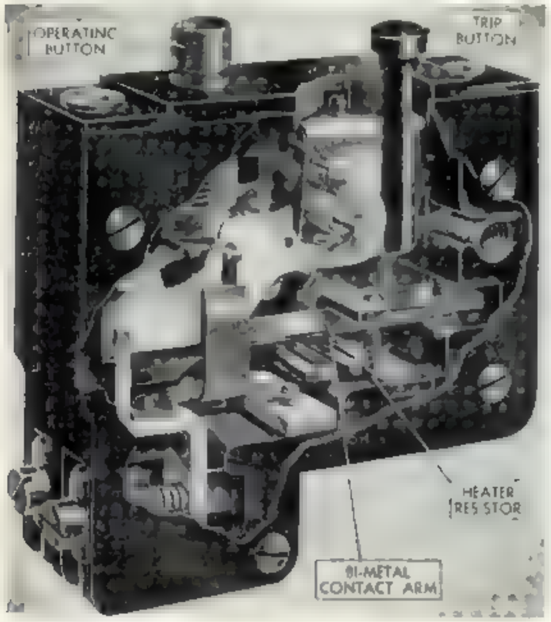
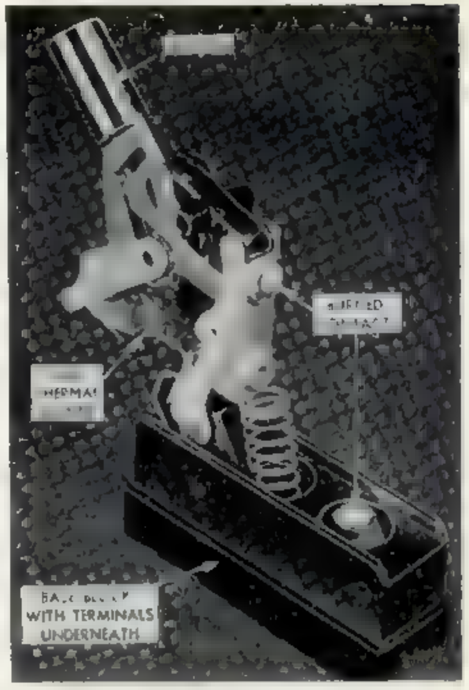


FIG. 10.32. *Sectioned view of a push-button-operated thermal trip switch.*

FIG. 10.33. *Partially dismantled thermal trip switch which has been damaged by heavy overload.*



Circuit-breakers which are tripped by a thermal relay are subject to the time delay inherent in such relays, which is approximately inversely proportional to the magnitude of the fault current. A curve relating operating time and current for a circuit-breaker having a thermal tripping relay is practically the same as that of the relay itself (see Fig. 10.26), since the delays incurred by the circuit-breaker mechanism and arc extinction are relatively small. Very fast operation is unattainable with thermally operated circuit-breakers and magnetically operated tripping relays are used where this feature is required.

Thermal Trip Switches. This is the name given to a combined switch and thermally operated circuit-breaker. It is a component which has received considerable development for aircraft systems and is now available for both 28 and 112 volts d.c. Fig. 10.32 shows a sectioned photograph of a push-button-operated thermal trip switch for 28-volt circuits which is available in ratings up to 20 amp. It occupies a panel space approximately $2\frac{1}{4} \times \frac{3}{4}$ in., weighs 3 oz. and is designed so that a number can be mounted side by side to form a bank. Another type, rated to carry 35 amp., and which has been subjected to a fault current of about 1,650 amp., is shown in Fig. 10.33. It opened after 21 milli-seconds, successfully checking the fault, but its thermal element was fused and its contacts severely burned.

Contacts. Contact materials should have low contact resistance, high resistance to erosion by arcing, resistance to corrosion and should not weld. In components which do not sustain serious arcing, fine silver is generally used since it has low contact resistance and is satisfactory in other respects. Sintered silver-nickel materials have greater resistance to arcing but higher contact resistance and are frequently used in circuit-breakers. For resistance to severe arcing, silver-tungsten materials are used but owing to their high contact resistance they are generally used only for arcing contacts. Contacts

of silver-graphite are used where high current pulses are expected which are likely to cause contact welding. Pure silver contacts have been found unsatisfactory for low voltages and small currents owing to the formation of corrosion films. Rhodium or rhodium-plated contacts, or hermetically sealed contacts, are preferable in circuits where the voltage across the contacts before "make" is less than six volts.

FUSES

The fuse is attributed to Edison in 1880 who regarded it as a "weak link" which protected the conductors in a circuit. Later other qualities were recognized and developed, principally: (*a*) particular shapes of time/current characteristics (t/c-ch.); (*b*) current limiting (this is the breaking of a fault current before it has reached its maximum or prospective value); (*c*) the ability to break large fault currents without explosion. Similarly, the following defects were minimized: (*a*) the effects of ambient temperature on fuse characteristics; (*b*) ageing.

Fuses have been used in aircraft since the introduction of electrical systems, but in the early systems of limited capacity their characteristics were not critically examined. The need to replace them after faults and to carry spares was considered a nuisance but their performance was generally adequate. During the early part of the second world war thermal trip switches were developed to a degree of reliability sufficient to challenge the position of the fuse. They were also attractive because they are quickly reset and replace two components, a switch and a fuse. A number of U.S.A. and German aircraft used large banks of thermal trip switches and relatively few fuses. Subsequent increases in the quantity of installed equipment and the introduction of three-phase systems increased the number of protective components required and the fuse, owing to its simplicity, small size and light weight, has partially regained favour. Considerable savings in weight and panel space have been obtained by using fuses of link form, as shown in Fig. 10.34,

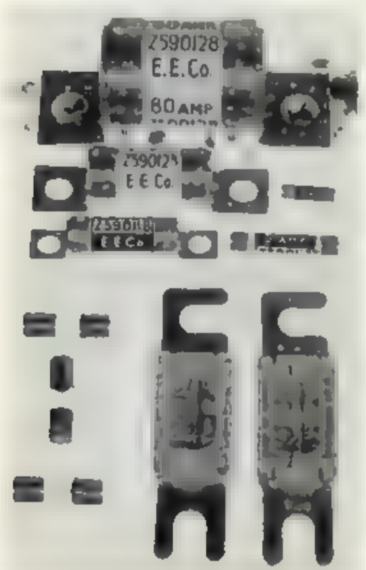
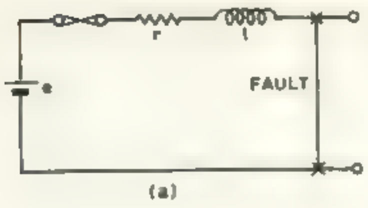


FIG. 10.34. *Selection of aircraft fuses:* (top) *H.R.C. fuses;* (bottom, left) *simple fast-operating air fuses;* (bottom, right) *slow-operating air fuses.*



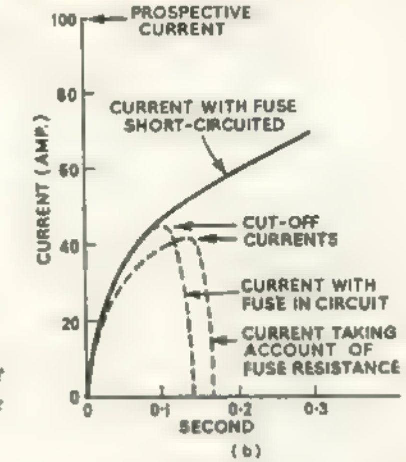


FIG. 10.35. (a) *Faulted d.c. circuit with fuse protection.* (b) *Showing the cut-off action of a fuse.*

instead of cartridge fuses which require a holder. A further reason for the increased use of fuses is that the fuse can interrupt the large fault currents which are possible from modern power systems without difficulty, whereas the simpler types of thermal trip switch can only interrupt smaller currents. An installation using link-type air fuses is shown in Fig. 10.39; they are located at the top, left of the illustration.

TERMINOLOGY AND CHARACTERISTICS

Current Rating. This is defined as the maximum current which a fuse can carry indefinitely without operating, that is, fusing or blowing.

Minimum Fusing Current. The minimum current at which a fuse will operate.

Fusing Factor. This is the ratio Minimum fusing current/Current rating, which usually has a value between 1·5 and 2·5, the higher value being characteristic of fuses with a small current rating.

It should be noted that between the rated current and minimum fusing current there is a current range in which a fuse cannot be depended on either to operate or to carry a current. In general, prolonged use near the minimum fusing current causes ageing and the fuse will eventually operate, whereas occasional moderate overloads, currents a little in excess of the rated current, may be expected to have little effect. Ageing may be defined as processes which modify the fuse characteristics, reducing the minimum fusing current and current rating. It may be minimized by using non-oxidizing elements, such as silver-plated copper or tin, and by designing for low working temperature.

Cut-off. In the circuit shown in Fig. 10.35 (*a*), if the fuse is short-circuited, the fault current reaches a final value of e/r amp. which is called the

prospective current of the circuit. The current rises at a rate determined by the ratio *l/r* and the value of prospective current. The form of the first part of the current/time curve is shown by the full-line curve in Fig. 10.35 (*b*). If, however, the fuse is not short-circuited, the fuse may operate before the current reaches its prospective value. This is indicated by the left-hand broken-line curve of Fig. 10.35 (*b*). The value of current at which a fuse operates is called the cut-off value, and in many circuits this is significantly less than the value of prospective current.

A more precise representation of the current/time curve is given by the other broken-line curve of Fig. 10.35 (*b*). This form arises because the fuse resistance increases as the fuse is heated. Immediately before melting, the resistance of a copper fuse is over five times higher than normal. It is estimated that just before melting a fuse resistance may be up to 20 per cent of the total circuit resistance in a low-voltage circuit which is subjected to a low-resistance fault. After melting, the fuse resistance increases rapidly and arcing follows. The duration of arcing in d.c. circuits depends on the voltage and inductance/resistance ratio of the circuit but is usually less than a few milli-seconds. In a.c. circuits the current zeros, which occur twice every cycle, substantially control arcing. When arcing begins, the fault current is usually falling rapidly. The current-limiting action of a fuse is caused by its rising resistance and, since it reduces the maximum fault current, is a minor advantage of a fuse over a circuit-breaker.

It should be noted that some fuses, which have no special means of arc extinction, are called current limiters. They are also known as air fuses. Although the name might imply otherwise, these fuses have no outstanding current-limiting or cut-off action.

Arc Extinction. In high-voltage work, elaborate methods have been developed to extinguish arcs in fuses. Owing to the relatively low system

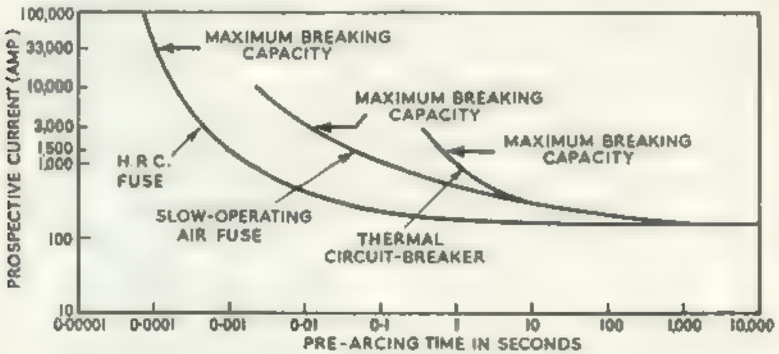


FIG. 10.36. *Time/current characteristics of fuses and thermal circuit-breaker, designed for use in aircraft.*

voltages, aircraft fuses either have no special means of arc extinction or the fuse element is packed in an inert granular material. Generally, fuses of the latter type are used in the main distribution circuits of all except 28-volt d.c. systems.

Current-breaking Capacity. This is the minimum current which a fuse may be expected to break without explosion or shattering, and is usually specified in conjunction with a maximum circuit voltage. Some aircraft fuses have breaking capacities up to about 30,000 amp. at voltages substantially higher than the highest system voltages. These are termed high-rupturing-capacity (H R.C.) fuses and employ the simple method of arc extinction described in the previous paragraph. Such a breaking capacity is almost certainly greater than is really necessary and it is expected that some reductions of weight and size will be achieved by accepting smaller breaking capacities. Current limiters have breaking capacities up to about 3,000 amp. at 30 volts d.c.

Shape of the Time/Current Characteristic. Fig. 10.36 shows time/current characteristics (t/c-ch) of typical H.R.C. and air fuses. The times shown are pre-arcing times and the currents prospective circuit currents. The curves are, strictly, only true for circuits having a particular time constant or inductance/resistance ratio, but may be taken as applicable to typical aircraft fault conditions. The considerable difference between the characteristics of the two types of fuse is brought about by design of the fuse element. The H.R.C. fuse is as fast-operating as it is practicable to make a fuse and the air fuse is about as slow as is practicable. Under major fault conditions the air fuse is at least as fast as a fast circuit-breaker and the H.R.C. fuse is very much faster. The relatively slow operation of this air fuse is a useful characteristic in circuits carrying occasional current surges, such as motor-starting currents. For comparison, the t/c-ch. of a thermal circuit-breaker is also plotted in Fig. 10.36. It can be seen that the air fuse t/c-ch. falls midway between this and that of the H.R.C. fuse. Slow operation is not necessarily a characteristic of air fuses but most of those currently being installed are of this type.

The design features which modify the shape of a t/c-ch. may be understood if it is appreciated that for time intervals of less than about 100 milli-seconds, most of the heat generated in a fuse element is confined within the element and raises its temperature, whereas over longer time intervals a significant amount of heat is lost to the surroundings. This means that the shape of the section *ab* of the t/c-ch. shown in Fig. 10·37 is determined mostly by the thermal capacity of the element, and the section *bc*, mostly by the heat losses to the surroundings.

A simple illustration of an application of these principles is to be found by comparing two fuse elements of identical metal and equal cross-sectional

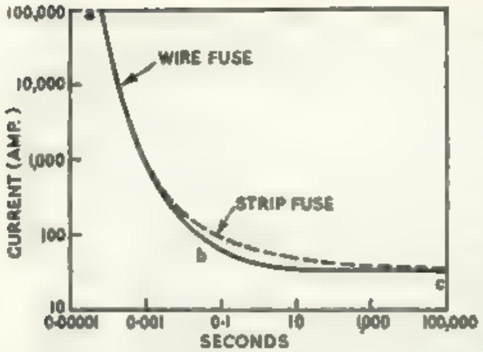


FIG. 10.37. *Time/current characteristics of fuses of identical metal and equal cross-sectional areas.*

areas, one of wire and the other of strip. Because both have the same resistances and thermal capacities, heats generated and temperature rises will be identical for short time intervals and sections *ab* of the t/c-chs will be identical for each fuse. Over longer time intervals, however, the strip element will lose heat more readily owing to its larger surface area, and it will be slower than the wire element. The forms of t/c-ch. of each element are shown in Fig. 10.37. Merging of the curves at low currents arises from the form of presentation, which does not distinguish between the operating times at low currents.

A further modification to reduce the thermal capacity of part of the strip element and make it operate faster over the section *ab*, is to reduce the width of the strip over a short length. The narrow part of the element has little effect on section *bc* because heat is conducted freely to the full-width parts of the element and the working temperature of the constriction is only a little higher than that of the rest of the element. One type of air fuse, shown in Fig. 10.34, uses a strip element which is integral with two large connecting lugs. These lugs act as heat sinks and make the fuse very slow-operating over the section *bc* of its t/c-ch. A useful feature of these fuses, also known as current limiters and fuse links, is that the condition of the element may be determined by visual inspection. The other type of air fuse shown is relatively fast but has only a small current-breaking capacity. It is available in current ratings from about 30 amp. down to fractions of an ampere. It is generally used only where the possibility of a large fault current is precluded by circuit impedance, or where adequate protection is provided by other means. The H.R.C. fuses, shown in Fig. 10.34, have been extensively used in 112-volt d.c. systems and 200-volt a.c. systems and are fast-operating fuses with more than adequate rupturing capacity.

DISTRIBUTION SYSTEMS

THE function of a distribution system is to ensure that the power available at the terminals of the power sources is also available at the terminals of the power-consuming equipment. This function is complicated, under abnormal conditions, by the following requirements.

1. Power source failures must not cause power-consuming equipment to be deprived of power unless the total power demand exceeds the available supply.

2. Faults on the distribution system should have the minimum effect on its functioning. They should also constitute the minimum possible fire risk and cause the least possible damage.

3. Faults in power-consuming equipment must not endanger the supply of power to other equipment.

BUSBARS

The first requirement is met, in most power systems, by paralleling all the generators and arranging for faulty generators to be disconnected from the system. Although this has been the accepted practice for all d.c. systems and is likely to be continued in constant-frequency a.c. systems, it is not without disadvantages, and a minority of engineers have championed the cause of non-paralleled systems. The most simple way of connecting generators in parallel is indicated in Fig. 10.38 which shows all the power being channelled through a single terminal, *A*. Such a system is completely de-energized if point *A* is accidentally short-circuited to earth. In practice, the terminal *A* would have appreciable size and is likely to be one or more metal strips, or busbars, carrying a number of terminals for incoming and outgoing leads. Experience has shown that the probability of such a fault is small but not insignificant. It can arise from such things as a nut or small metal component becoming wedged between live metal and earth, or from faults in circuit-breakers connected directly to the busbars. Protection for the busbar and live parts connected directly to it can only be mechanical, and it is considered necessary to secure additional reliability by using split busbars or emergency busbars.

Mechanical Protection. In most aircraft, busbars are of such dimensions that it is practicable to enclose them. This has been done with insulating material, and with metal insulated internally and from the airframe. Non-metallic containers are generally of fairly light construction. Fig. 10.39 shows part of the main 28-volt d.c. busbar of the Vickers "Vanguard" which is partly protected by a transparent cover.

Metal containers, insulated from the airframe, permit at least one fault between busbars and the container without causing a failure. The container

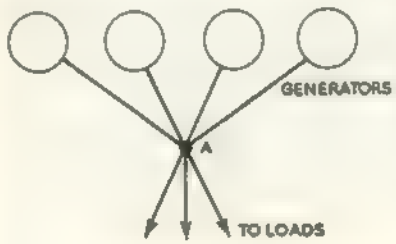


FIG. 10.38. *Illustrating the vulnerability of a single-busbar system.*

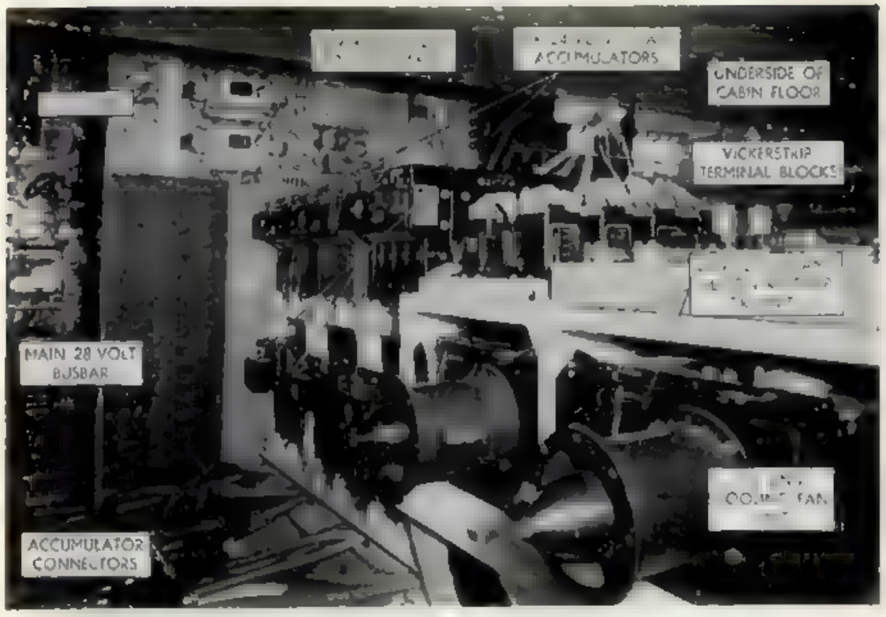


FIG. 10.39. *View inside the electrical bay of an early Vickers "Vanguard".*

may be connected to the airframe by a fuse, with an indicating lamp in parallel, so that in the event of a fault the fuse operates and the indicator lamp lights. Earthing the container through a fuse may be necessary for the reasons given earlier in this chapter (see *Bonding and Earthing*).

Where d.c. systems of different voltages are installed in one aircraft, the busbars are usually accommodated separately. Three-phase busbars require protection, not only against earth faults, but also against interphase faults.

SPLIT BUSBARS

A split busbar scheme is indicated in Fig. 10.40 (*a*). With overcurrent protection at each end of the interconnecting feeder, only half of the system is affected by a busbar earth fault. By distributing the essential equipment, which is duplicated, and the loads which can be conveniently divided, such as lighting, between the two busbars, a satisfactory system can usually be devised. The supply for essential equipment which is not duplicated is provided from either busbar by a selecting contactor.

Faults on the interconnecting feeder, either open-circuit or short-circuit, do not affect the normal operation of the system. The feeder carries no current except that arising from unequal loading and in the event of a generator failure. The ultimate in split busbar layout is shown in Fig. 10.40 (*b*) where

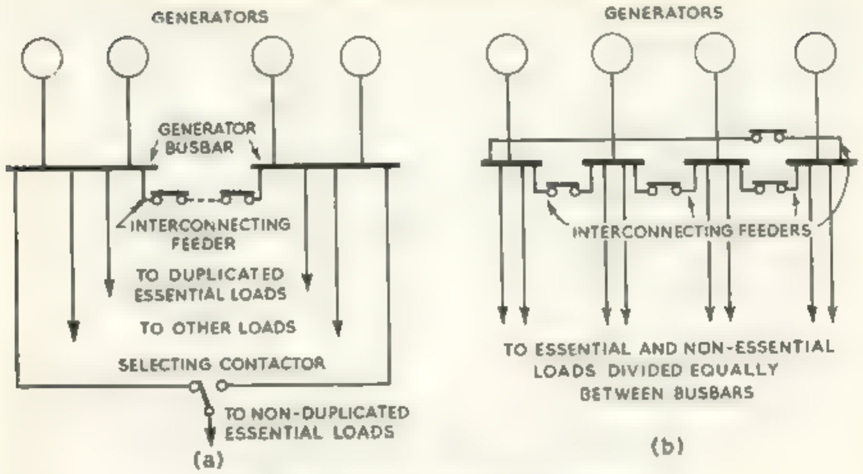


FIG. 10.40. *Practical split-busbar systems.*

each generator has its individual load busbar. A constant-frequency a.c. system of this type is discussed in Chapter 11.

EMERGENCY BUSBARS

Fig. 10.41 (*a*) indicates the essentials of a system having an emergency busbar. Power for the emergency busbar, which is completely separate from the main busbar, can be selected from either of two generators and from the accumulator. Selection is from one port and one starboard generator to minimize the possibility of losing both sources simultaneously. Only the most essential loads are supplied from the emergency busbar and the demand is substantially less than the output of one generator so that, in the event of failure of all generators, the accumulator can supply the demand for the time necessary for making an emergency landing.

SEPARATE GENERATOR AND LOAD BUSBARS

Some large aircraft have employed separate generator and load busbars as shown in Fig. 10.41 (*b*). The interconnecting feeder between the generator busbars serves the same purposes and behaves in the same way as the interconnector in the simple split busbar system described earlier. Its functions are duplicated by the interconnecting feeder between the load busbars but the addition of this interconnector gives the advantage that some power is supplied to both load busbars in the event of a failure of either generator busbar. Distribution of essential loads between the two load busbars is, however, still necessary to cover the case of a load busbar fault. Failure of any one feeder does not affect the normal operation of the system. An

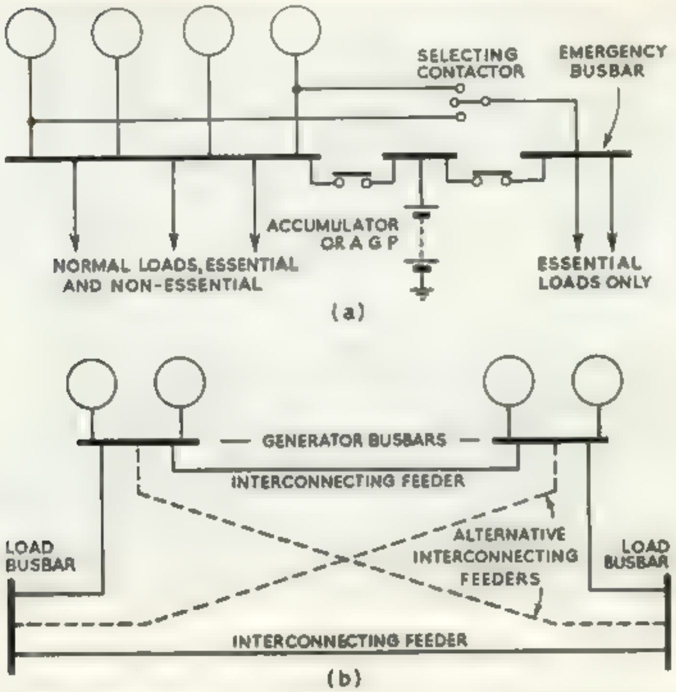


FIG. 10.41. (a) *System having an emergency busbar.* (b) *System having a separate generator and load busbars.*

alternative layout for the interconnecting feeders is indicated in Fig. 10.41 (*b*) which can be designed so that in normal operation all feeders carry significant currents.

The primary considerations in positioning busbars in civil aircraft are cable economy and access for servicing. In military aircraft the vulnerability of busbars has sometimes also influenced the choice of position. For cable economy it is necessary that the busbars should lie on or near to the route from the generators to the centre of the loads. A common position in civil aircraft, which satisfies this requirement fairly well, is under the main cabin floor about midway along the fuselage. The "Vanguard" 28-volt d.c. busbar, part of which is shown in Fig. 10.39, is mounted in approximately this position.

LOAD TRANSFER SWITCHING

In systems using variable-frequency a.c. power parallel operation is not possible. The only method of ensuring a supply to power-consuming equipment in the event of a generator failure is to install a selecting contactor, as

shown in Fig. 10.40 (*a*), to enable the power supply for any load or group of loads to be selected from two or more generators. It is usual to provide this facility only for the most important loads and it happens that variable-frequency loads are often relatively unimportant. Thus the amount of load transfer switchgear installed and the number of selections offered are usually limited. Notice that the transfer switching in the paralleled system of Fig. 10.40 (*a*) is required only in the unlikely event of a busbar fault, but in variable-frequency a.c. systems it is required also in the event of failures of generators or drives.

PROTECTIVE METHODS

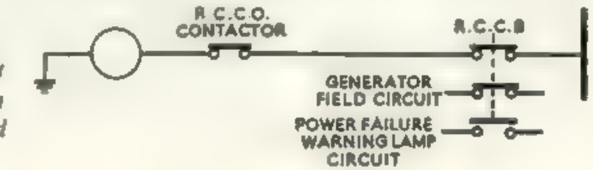
Items 2 and 3 of the requirements of a distribution system (see page 221) are met by various methods of protection. The following sections describe methods which are used for the several main parts of systems, both a.c. and d.c. Some examples of the applications of these methods in each type of system are given in Chapter 11.

Generator to Busbar. This part of a system, which includes the generator, is liable to experience the following faults: (1) insulation breakdown; (2) open circuit; (3) low voltage; (4) high voltage; (5) reversed polarity (d.c. only); (6) low frequency (a.c. only); (7) high frequency (a.c. only); (8) incorrect phase sequence.

Insulation breakdown, whether to earth or between the lines of an a.c. system, allows current flow from two sources, the generator and the busbar. Exceptions to this are when the generator is energized but not connected to the system, and the generating channel of a rectified a.c. system in which the rectifier prevents current flow from the system to the fault. In the latter case the argument applies only to the feeder, if one is used, between the rectifier and the busbar.

A very widely used method of protection for d.c. systems is to fit a reverse-current-circuit breaker (R.C.C.B.) as close to the busbar as possible. This type of circuit-breaker has a built-in relay which is sensitive to reverse current and which operates the trip mechanism of the breaker. It is insensitive to forward current. Auxiliary contacts of the circuit-breaker serve to de-energize the generator by opening its field circuit and operate a power-failure warning lamp. The circuit is represented in Fig. 10.42 and a typically positioned R.C.C.B. may be seen in Fig. 10.39.

FIG. 10.42. *Reverse-current circuit-breaker protection of a d.c. generator and feeder.*



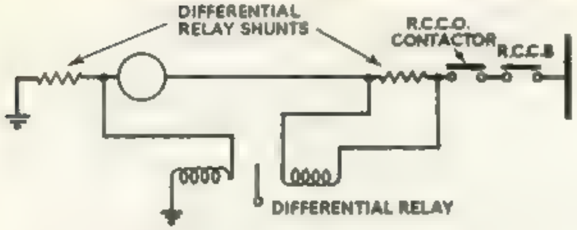


FIG. 10.43. *Differential-current protection of a d.c. generator and feeder.*

Co-ordination is necessary between the R.C.C.B. and reverse-current cut-out (R.C.C.O.) in d.c. systems in order to ensure that the R.C.C.O. is not burdened with the duty of a circuit-breaker. This is discussed in Chapter 11 (see *Co-ordination of the R.C.C.O and R.C.C.B.*).

Some of the shortcomings of this simple scheme are:

1. If an earth fault exists within the generator or between the generator and the R.C.C.O., before the generator is excited, the R.C.C.O. does not close and the R.C.C.B. does not operate. Thus the generator, if it builds up, feeds current into the fault. The probability of build-up is increased if a field "tickling" circuit is used.

2. After the R.C.C.B. has operated in the event of a fault in the same part of the circuit as for 1, the generator may feed current to the fault owing to the effects of residual magnetism and, if fitted, a series field winding.

An alternative method of protection is indicated in Fig. 10.43. This employs a differential current relay which operates, when the currents in its two coils are unequal, to trip the R.C.C.B. Defect 1 of the method previously described, is overcome by the differential relay, but the second defect remains. The circuit-breaker at the busbar is still fitted with a reverse-current relay so that it operates in the event of the R.C.C.O. contacts becoming welded and allowing reverse current to flow when the generator is de-energized. Despite the necessity for series resistors and the long leads from these components to the differential relay, differential protection shows signs of increasing application. The use of part of the generator series windings instead of one of the series resistors is possible but, if nuisance tripping is to be avoided under transient conditions, the time constants of the two differential relay coil circuits must be similar.

Differential current protection is also applied to a.c. systems as indicated in Fig. 10.44. This gives protection in the event of line-to-earth or line-to-line faults on the feeders and equipment between the current transformers. The use of current transformers instead of series resistors is advantageous because lower losses are incurred and also because the relay circuit is isolated from the earth. Thus at least one earth fault is possible in the circuit containing the transformer secondary windings and relay coils, without impeding its operation. Notice that the differential action is secured by the

current transformer circuit and that the protective circuit operates when one or more relay coils are energized.

Another method for protecting a.c. lines, the use of which has been confined to rectified a.c. systems, is described in Chapter 11 (see *Short-circuit between A.C. Lines*).

So far no mention has been made of any device to limit the forward current delivered by a generator to the system. Such devices have been deliberately omitted in many modern systems because it is felt that if the system demands current, whether for fault clearing or because a number of generators are inoperative, it is preferable that the generator should be overloaded rather than that the system should be deprived of power. Where short-time overload is expected to render a generating channel inoperative, as in the case of a d.c. output of a rectified a.c. system, over-current protection is normally provided.

Open circuits of the generator to busbar feeders are generally dealt with by the protective circuits as a special case of under-voltage. Other causes of under-voltage are field circuit faults and loss of generator drive.

Under-voltage Protection. Under-voltage occurs in the course of operation when the generators are shut down, and the flow of reverse current from the system to the generators is a normal indication of this condition. In simple d.c. systems, reverse current is sensed and checked by the R.C.C.O. and under-voltage protection is not a primary necessity. It has been used for secondary functions such as disconnecting the differential coil of the differential type R.C.C.O., described in Chapter 11 (see *Reverse-current Cut-outs*).

If, however, the system is fitted with an equalizing method of load sharing, as described in Chapter 11 (see *Regulator Equalizing Coil, Constant-voltage Method*), and all modern systems are, under-voltage protection is necessary and it is inevitably interconnected with the load-sharing circuit. This is because the load-sharing circuit acts to raise the voltage of any

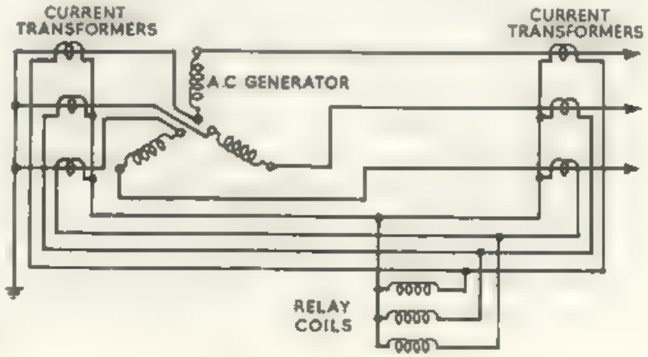


FIG. 10.44. *Differential - current protection of an a.c. generator and feeder.*

generator which is generating low voltage and to lower that of all the others. At least three classes of under-voltage faults can be distinguished.

1. When a generator is operating at subnormal voltage and the load-sharing circuit succeeds in preventing reverse current. In this case the system voltage is reduced and a protective circuit is needed to clear the faulty generator from the system.

2. When the generator voltage is so low that the load-sharing circuit cannot prevent reverse current. In this case the R.C.C.O. removes the generator from the system, its auxiliary contacts disconnect the associated equalizing circuit and the system voltage returns to normal.

3. When the generator circuit is not continuous, as in the case of an open-circuited generator-to-busbar feeder. Since reverse current cannot flow, definite voltage-type R.C.C.O's may remain closed if the generator voltage is normal, and the system voltage would be reduced by the load-sharing circuit. As for case 1, the load-sharing circuit of the faulty generator must be opened.

The additional protection required for case 1 and case 3, can be provided by a polarized relay in the load-equalizing circuit of each generator, since the direction of current in the equalizing coil of the faulty generator is opposite to that of currents in all the other equalizing coils. This relay can be arranged to trip the R.C.C.B., which by de-energizing the generator would release the R.C.C.O. and disconnect the equalizing circuit, when the equalizing current exceeds a predetermined magnitude and is of such a direction that it tends to raise the generator voltage.

A serious disadvantage of arranging the under-voltage relay to trip the R.C.C.B. is that the generator is removed from the system and will not automatically return. This is undesirable because, if the flow of equalizing current arises from a generator operating at excessive voltage, all the sound generators can be removed from the system and, after operation of the over-voltage protection, the system is left without a supply. It is therefore preferable to arrange that the under-voltage relay only disconnects the load-sharing circuit and allows the R.C.C.O. to disconnect the generator from the system. A method of ensuring this sequence of operation is described in Chapter 11 (see *Co-ordination of the R.C.C.O. and R.C.C.B.*).

A different arrangement, which is sometimes used, has the under-voltage relays sensed so that they operate when the equalizing current is tending to lower the generator voltage and connected so that they short-circuit the associated equalizing coil. With this arrangement the generator having a low-voltage fault is presented with a sudden increase of system voltage as the load-sharing circuit becomes ineffective, owing to the short circuiting of the equalizing coils of all the other generators, and is disconnected from the system, as previously described, by reverse current. This covers case 1.

Case 3 is covered, however, if a differential-type R.C.C.O. is used, since this would release in the event of an open-circuit generator feeder. This arrangement of under-voltage relays has an advantage in dealing with over-voltage faults, as described in the next section.

In a.c. systems the equivalent of reverse current, arising from low generator voltage, is currents in quadrature with the corresponding phase voltages. There is no concise equivalent of the R.C.C.O. to sense these currents and disconnect the generator, but the same function is performed by a combination of circuits and components. A currently used scheme has a circuit similar to that which is shown in Fig. 11.26, feeding a voltage regulator sensing coil. This circuit develops an output voltage which increases as the generator delivers quadrature lagging current, or reactive power, and vice versa. The under-voltage relay is supplied from the output of the three-phase bridge rectifier of this circuit. It is arranged to release when the output voltage of the circuit is at a low value, corresponding to a system voltage of about 85 per cent normal, when there is a flow of quadrature lagging current into the generator of about half its current rating, or when an equivalent combination of these two conditions occurs. The under-voltage relay is connected so that, on operation, it will trip a circuit-breaker in the generator feeder and de-energize the generator.

A slight variant of this scheme uses a three-phase torque switch as a combined under-voltage relay and phase sequence detector. This is supplied from the input to the rectifier of the circuit shown in Fig. 11.26. It consists of a small three-phase induction motor which is controlled by a clock-type spring so that after rotating a few revolutions the spring and motor torques are equal and the motor is stalled. At normal supply voltage the motor operates one or more pairs of contacts just before it is stalled. A typical setting is such that the contacts are closed when the voltage is raised to 90 ± 4 per cent, and opened when it is lowered to 83 ± 4 per cent of the nominal value. An eddy-current brake on the motor, consisting of a conducting disk rotating in the magnetic field of a small permanent magnet, serves to damp the movements of the motor caused by short-duration voltage and frequency fluctuations. Incorrect phase sequence causes reversed rotation of the motor against a stop, and failure of one line voltage has the same effect as reduced three-phase voltage.

Over-voltage Protection. Like under-voltage protection, this is closely linked with the load-sharing circuit in all systems having equalizing methods of load sharing. A widely used type of relay for d.c. systems has two coils, one energized from the generator positive line and the other by equalizing circuit current. The equalizing circuit current passed through the over-voltage relay of a generator operating at excessive voltage, tends to operate the relay. Operation occurs as a result of the combined effect of over-voltage and

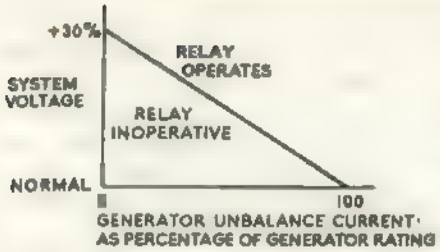


FIG. 10.45. *Illustrating the operating characteristics of an over-voltage relay.*

equalizing current, as indicated in Fig. 10.45. The voltage coil of this type of over-voltage relay is often connected in series with a non-linear resistor, the resistance of which decreases as the current through it is increased. With this arrangement the voltage coil experiences a relatively large increase of voltage when a small increase occurs on the generator positive line. The relay is connected to trip the R.C.C.B. which in turn de-energizes the generator. Another scheme uses polarized relays which are sensitive only to the equalizing circuit current, like the under-voltage relays described in the previous section. These are also connected to trip the R.C.C.B.

The particular arrangement of under-voltage relays, mentioned in the previous section as being helpful during over-voltage conditions, operates as follows. The under-voltage relay of a generator delivering excessive voltage operates, and short-circuits the equalizing coil, because the equalizing current is tending to lower the voltage of that generator. This allows a sudden rise of the generator voltage which causes a further increase of the equalizing current and decisive operation of the over-voltage relay. The latter may be of either the polarized or double-coil types.

If the under-voltage relay had operated for some reason other than that caused by an over-voltage generator, such as a fault in the equalizing circuit, short-circuiting the equalizing coil would not substantially alter the equalizing current and the over-voltage relay would not operate. System operation would probably continue, but without equalizing. The advantages of this arrangement are that if an over-voltage fault is present, action is taken to clear the fault when the equalizing circuit current indicates only a moderate degree of unbalance, rather less than that occurring when a generator is shut down. Also, this is achieved without the need for a very critical setting of the over-voltage relay, because the time interval between the operation of the under- and over-voltage relays is likely to be short, and a higher voltage can be permitted for this interval than could be tolerated continuously.

It has been explained that, in the event of under-voltage conditions, the under-voltage relays of all the sound generators operate to cause reverse current and remove the under-voltage generator from the system. Short-circuiting of the equalizing coils of these generators does cause some increase in the unbalance conditions but this is insufficient to operate their over-voltage relays.

A simple over-voltage relay scheme for an a.c. system consists of single-coil relays energized from the rectifier output of the same circuit (see Fig. 11.26) as the under-voltage relays described in the previous section. These relays are connected, as were the under-voltage relays, to disconnect and de-energize the generator and disconnect the equalizing circuit.

Another type of over-voltage protection, designed to give more precise control and to provide a time delay which is inversely proportional to system voltage, is shown in Fig. 10.46. The circuit is energized from the same source as before. The time constant of the resistor and capacitor, *R* and *C*, is selected to give a delay of several seconds under slightly abnormal conditions, diminishing to a few hundred milli-seconds at a voltage corresponding to a system voltage about 30 per cent above normal. It will be recalled that the circuit from which the relay circuit is energized is sensitive to both system voltage and reactive load unbalance. Time delays are often incorporated in over-voltage protection arrangements, both in d.c. and a.c. systems, in order to avoid nuisance tripping during voltage surges which occur in the course of normal operation.

Reversed Polarity. This can arise from incorrect installation or from reversal of generator residual magnetism after heavy fault currents. A polarized type of R.C.C.O. is generally a fair safeguard against the connexion of a reversed generator to the system.

Under-frequency Protection. The tendency of a generator to develop subnormal frequency is opposed by the real load-sharing circuit, described in Chapter 11 (see *Equalizing, Constant-frequency Method*), and, as with under-voltage, gives rise to equalizing currents which indicate the faulty generator by their direction. Polarized relays in the equalizing circuits of each generator can therefore be used to detect and isolate the faulty generator.

A more direct method of detection is to use a mechanical or hydraulic under-speed detector, coupled mechanically to the drive. This is possible, without causing a serious reduction of system frequency or loss of synchronism, if the generators are fitted with sprag clutches or "free-wheels" allowing them to rotate at higher speeds than the drives. If this is done, a generator with a faulty drive operates as a synchronous motor when its

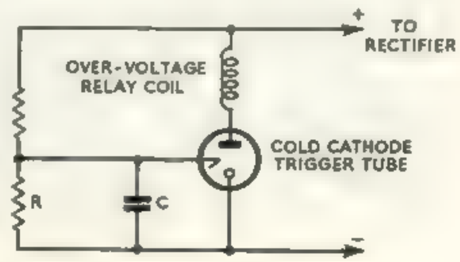


FIG. 10.46. *Over-voltage protection circuit having an inverse time delay. It is supplied from the rectifier circuit shown in Fig. 11.26.*

drive speed falls below that corresponding to the system frequency. A typical speed for the operation of under-speed detectors is 15 per cent below normal, and they are connected to isolate the generator from the system. As with under-voltage in a d.c. system, under-frequency in an a.c. system occurs during normal operation when the system is shut down.

Over-frequency Protection. This can be detected by either of the methods described for under-frequency detection. The situation is different, however, because a generator with an overspeeding drive may be constrained to take on the entire real load of the system. At the same time the system frequency must rise and remain proportional to the drive speed. Relief may come from failure of the shear section of the generator shaft if the system load is great enough. Detection by drive speed is therefore not satisfactory as a means of avoiding a major system disturbance although it is considered desirable as an ultimate safeguard. Detection by polarized relays in the equalizing circuits is also necessary and these relays are connected, not only to isolate and de-energize the generator, but also to set the drive speed control to minimum.

Phase Sequence. This is analogous to reversed polarity in a d.c. system but it can arise only from incorrect installation. Detection is most easily achieved by using a three-phase torque switch, which is sensitive to phase sequence in addition to being sensitive to voltage, as an under-voltage relay.

ACCUMULATOR TO BUSBAR

This relatively simple part of the system is liable to the following faults: (1) insulation breakdown; (2) open circuit; (3) reversed polarity; (4) battery failure. Before discussing these faults it may be useful to consider how the conditions in this part of a system differ from those in the generator-to-busbar circuit. Firstly, an accumulator cannot be de-energized but only disconnected. Thus, to minimize the length of unprotected feeder an isolating

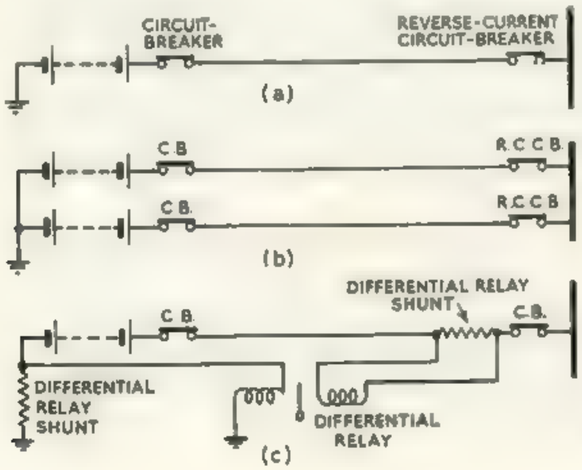


FIG. 10.47. *Protective schemes for accumulator-to-busbar feeders.*

circuit-breaker should be positioned as close to the accumulator as possible. Secondly, an accumulator is frequently the only source of power, in which case, an accumulator feeder earth fault cannot give rise to reverse current. Finally, an accumulator receives moderate reverse currents during normal charging but is required to be able to accept abnormal reverse currents in the event of a generator over-voltage fault, in order to restrain the system voltage.

Three schemes are shown in Fig. 10.47, which will be referred to as schemes (*a*) to (*c*). In each case the circuit-breaker near the accumulator serves as the normal means of disconnecting the accumulator from the system for servicing or storage. Because of this, contactors have been used in this position but, since they must break the fault current in the event of a feeder earth fault, they should have a current-breaking capacity, which is normally a characteristic of a circuit-breaker. Because of the high forward current required from the accumulator during engine starting, these circuit-breakers are not normally set to trip in the event of high forward currents but are tripped by the operation of their associated R.C.C.B's.

In schemes (*a*) and (*b*) the R.C.C.B's must be set to carry normal charging currents without tripping. They must also be delayed so that in the event of an over-voltage fault the over-voltage protection operates first. Both these requirements make the design and setting of the R.C.C.B's for prompt and decisive fault clearing, a little more difficult. Scheme (*b*) is advantageous because a flow of reverse current is ensured in the event of a feeder earth fault, even when all generators are disconnected, and is enhanced at other times, thus improving the operation of the R.C.C.B's. It also enables a lower minimum reverse current setting to be used because the charging current is subdivided. Scheme (*c*) has the advantage of not requiring co-ordination with the over-voltage protection equipment. Also the minimum operating current can be small because the circuit is insensitive to charge or discharge currents.

Open-circuit faults in the accumulator-to-busbar circuit have no undesirable consequences other than those arising from the loss of power supply. These are not to be dismissed lightly since there have been cases where generating systems have become unstable or could not be excited when the accumulator was disconnected, but no protective action is necessary in the accumulator-to-busbar circuit. The best safeguard against this type of fault is duplication, as in scheme (*b*), but this has not been widely adopted.

Although it is possible for accumulators to be charged with reversed polarity, it is usually considered sufficient precaution to use mechanically polarized connectors, such as the Cannon connector shown in Fig. 7.1. Accumulator failures do not usually occur suddenly, nor do they usually incur the flow of very large currents and the protective equipment of this part of the system is not designed to cover them.

MAIN FEEDERS

Main feeders are liable to be faulted by open- and short-circuit faults. Generally no protective action is deliberately taken on the former and in systems where duplicate feeders are provided it is necessary to check periodically to ensure that open-circuit faults have not developed. Short-circuit faults are cleared as quickly as possible.

Fig. 10.48 shows four schemes for main feeder protection. Scheme (*a*) uses a single unbalance current relay which operates when the difference between the currents in its two coils exceeds a predetermined value. The relay is arranged to open the circuit-breakers at both ends of the feeder. Thus a fault on either cable of the feeder causes the isolation of the complete feeder.

In practice the two cables cannot be identical and an unbalance current is normally present. It is approximately proportional to the total feeder current and operation of the unbalance current relay must be avoided, even with the highest current through the feeder. This occurs when an earth fault exists beyond the feeder, in a load circuit, and determines the minimum operating setting for the relay. When a fault exists in the feeder the unbalance current is determined partly by the position of the fault. For a fault of zero resistance, the unbalance current, i_u, is given by

$$i_u = \frac{2vr}{(r_c+r_1-r)(r_c+r_1+r)}$$

where v is the system voltage, and the other symbols represent resistances of components and cable lengths, as indicated in Fig. 10.48 (*a*). Thus if r is very small, i_u is also small and it can actually be zero if a fault occurs at the remote cable junction. Since there is a minimum workable setting for the relay there are some faults which cannot be detected by this scheme.

Scheme (*b*) in Fig. 10.48 is a development of the one shown in Fig. 10.48 (*a*), which overcomes this defect. The corresponding expression for unbalance current is

$$i_u = \frac{2v(r+r_c)}{(3r_c+r_1+r)(r_c+r_1+r)}$$

which is finite for any value of r and therefore for any fault position. As before, either relay operates both circuit breakers and isolates both cables. Neither scheme shown in Fig. 10.48 (*a*) or (*b*) gives any protection in the event of a fault on the load busbar.

Scheme (*c*) in Fig. 10.48, like those previously considered, uses a twin-cable feeder but with the difference that in the event of a fault only the faulted cable is isolated. Circuit-breakers 1, 2, 3 and 4 each contain their own operating relays and these are of different types. Those of circuit-breakers 1 and 4 are sensitive to current in both directions and are delayed so that those of circuit-breakers 2 and 3, which are sensitive only to reverse current, always operate first. If a fault occurs at the point shown in Fig. 10.48 (*c*) current flows

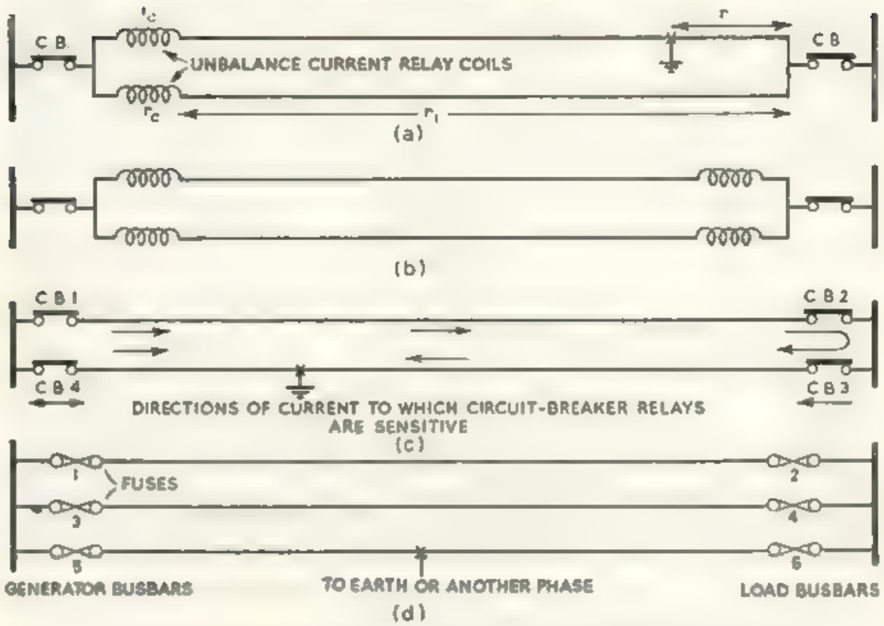


FIG. 10.48. *Protective arrangements for main distribution feeders.*

into the fault by the two routes indicated. Circuit-breaker 3 operates before 1 and checks the clockwise flow of fault current. Circuit breaker 2 does not operate because its relay is polarized and circuit-breaker 1 does not operate because its relay is time-delayed. Thus the upper cable is left in service. Subsequently circuit-breaker 4 operates to isolate the lower cable.

The scheme requires co-ordination between the relays of its circuit-breakers but no interconnexions. The settings of relays 1 and 4 must also be co-ordinated with the over-current protection of the load circuits so that they do not operate when a fault occurs beyond the feeder.

Although, theoretically, each of the preceding schemes can be applied to three-phase a.c. feeders this has not been done, partly because of the complexity involved and partly because the necessary equipment is not generally available in aircraft form. Fig. 10.48 (*d*) shows a scheme which has been applied to three-phase systems. Each phase feeder is, itself, triplicated, and fitted with H.R.C. fuses at each end. Thus a three-phase feeder, protected in this way, has nine cables and eighteen fuses. In the event of a fault to earth or between phases, as shown in Fig. 10.48 (*d*), fuses 5 and 6 carry substantially greater currents than any of the other fuses and therefore operate first, isolating the faulted cable and leaving the others in service.

It should be noted that a second fault on either of the cables remaining

in service is likely to operate all fuses and isolate the feeder. To cover the possibility of a second fault in one flight, feeders having four cables are necessary. The scheme is simple in that no co-ordination is required between the feeder fuses, but co-ordination is necessary with over-current protection beyond the feeder. It is practicable to use cables rated to carry half the total feeder current and, from the discussion in the Section on *Cable Ratings*, it follows that the three cables of a feeder may weigh less than one and a half times as much as the equivalent single cable.

A fuse checking procedure is necessary at frequent intervals since there may be no indication that a fault has occurred. Although mostly applied to a.c. systems, the scheme is equally workable in d.c. systems.

LOAD DISTRIBUTION BUSBAR-TO-LOAD

These circuits are at the extremities of a system and when subject to a short-circuit fault should be disconnected, whether the fault is in the feeder or the load. If a group of loads is supplied via one feeder, and continuity of supply is required in the event of one faulty load, the feeder should be terminated at a sub-load distribution busbar and each load should have individual protection from this busbar. The feeder from the main to the sub-busbar then has the nature of a main feeder.

Two types of protection for load feeders and loads are shown in Fig. 10.49. Fig. 10.49 (*a*) shows over-current protection with the circuit-breaker or fuse positioned as close to the busbar as possible. Examples of the positioning of such fuses may be seen in Fig. 10.39.

The over-current protector, whether fuse or circuit-breaker, should be capable of breaking the maximum short-circuit current available from the busbar. This requirement is more easily met with fuses than with circuit-breakers and, as may be seen in Fig. 10.39, they are sometimes used almost exclusively. In aircraft where load distribution busbars have been installed near crew positions, it has been practicable to use thermal trip switches to serve as on/off switches for the loads and also as over-current protectors.

The protective arrangements for small loads having small individual feeders from busbars of high potential fault current, need special consideration, since it is likely that the

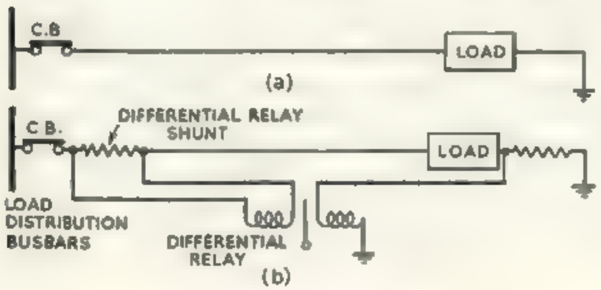


FIG. 10.49. *Two typical protection schemes for load circuits.*

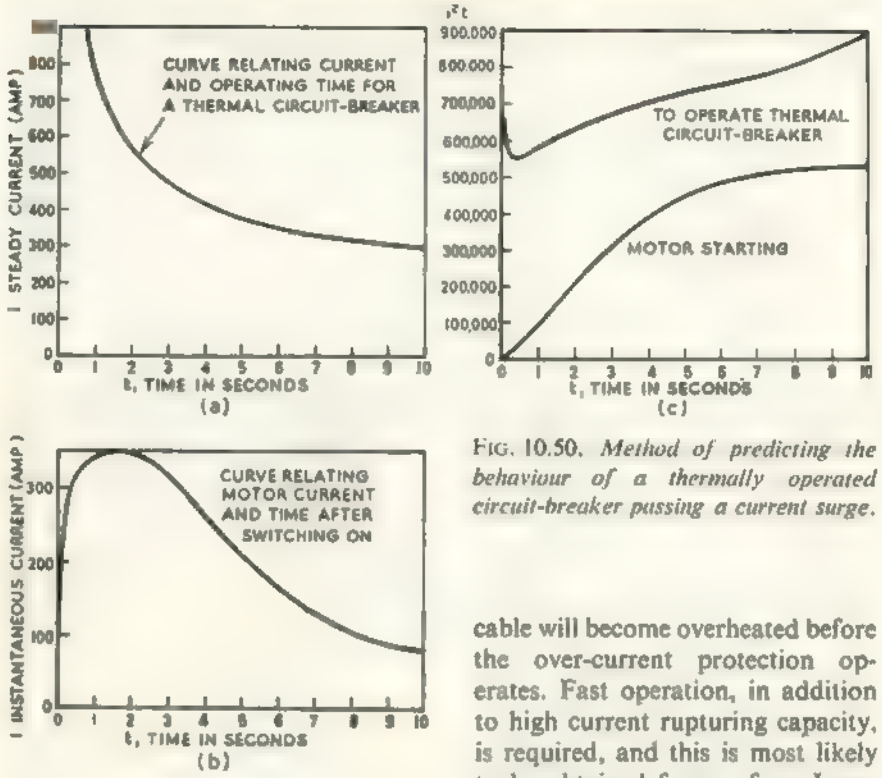


FIG. 10.50. *Method of predicting the behaviour of a thermally operated circuit-breaker passing a current surge.*

cable will become overheated before the over-current protection operates. Fast operation, in addition to high current rupturing capacity, is required, and this is most likely to be obtained from a fuse. Large loads, on the other hand, may demand currents when the system is operating normally, which are greater than the fault current which can occur when the system is energized only from an accumulator. In such a case, differential current protection, which is identical in principle with differential current protection of a generator, may be justified. Motor loads are sometimes difficult to protect because they demand a starting current several times greater than the full-load current. In such cases the delayed operation of a thermal-relay-operated circuit-breaker or a slow fuse may be used to advantage.

Selection of a thermal circuit-breaker to suit a load can be made from the time/current characteristics of the circuit-breakers and a curve relating motor current and time. It should be noticed that these two curves, of which examples are shown in Fig. 10.50 (*a*) and (*b*), are to be interpreted differently. Each point on the circuit-breaker time/current characteristic indicates a value of current which may be passed for a particular time, after which the circuit-breaker operates. Points on the curve of motor current indicate instantaneous values of current at particular times after switching on.

Table 10.3

TIME/CURRENT CHARACTERISTICS

Thermally Operated Circuit-breaker

t Time (seconds)	i Current (Amp.)	i^2 (Amp.)^2	i^2t (Amp.)^2 (Sec's)
0·68	900	810,000	551,000
1	762	581,000	581,000
2	562	316,000	632,000
3	477	228,000	674,000
4	421	177,000	708,000
5	383	147,000	735,000
6	355	126,000	756,000
7	334	112,000	784,000
8	320	102,000	816,000
9	309	95,500	860,000
10	300	90,000	900,000

Motor

t Time (seconds)	i Average current in preceding interval (Amp.)	δt Time interval (seconds)	i^2 Time interval (Amp.)^2	$i^2\delta t$ (Amp.)^2 (Sec's)	$i^2\delta t$ Total (Amp.)^2 (Sec's)
0·5	240	0·5	57,600	28,800	28,800
1	330	0·5	109,000	54,500	83,300
2	347	1	120,000	120,000	203,300
3	332	1	110,000	110,000	313,300
4	287	1	82,400	82,400	395,700
5	235	1	55,200	55,200	450,900
6	187	1	35,000	35,000	485,900
7	149	1	22,200	22,200	508,100
8	119	1	14,200	14,200	522,300
9	97	1	9,400	9,400	531,700
10	84	1	7,060	7,060	538,760

To determine whether or not circuit-breaker operation will occur, or to estimate the margin of safety, two curves proportional to the heat generated in the thermal relay element are required. These are (*a*) the heat necessary to operate the relay, and (*b*) the heat generated by the motor current, both curves relating heat and time. These curves can be derived from those previously mentioned as shown in Table 10.3. When plotted to the same scales and superimposed, an intersection indicates circuit-breaker operation and gives the time after switching on and, indirectly, the instantaneous current at which operation occurs. In the example, shown in Fig. 10.50 (*c*), operation does not occur. The margin by which it is avoided can be seen and compared with the tolerances of circuit-breaker and motor characteristics.

Another difficult case of motor overload is that of a motor which is demanding only a little more than its rated current. This may occur as a result of mechanical overloading or, in three-phase a.c. systems, from the loss of one supply phase. Protection in such cases is best obtained by building in to the motor a device known as a thermal protector. This is a thermal relay, sensitive to motor temperature and sometimes also to motor current, which serves as a circuit-breaker of low current rupturing capacity, usually two or three times full-load current. Manual and automatic resetting types are available and their dimensions are small enough to allow them to be built-in without serious penalties.

False Operation. Another kind of protection required in some load circuits is protection against unintended operation and accidental operation occurring as a result of faults. This is generally required in such circuits as those controlling propeller pitch, aerodynamic surfaces and trim tabs, flaps and undercarriages. In military aircraft it is also required in bomb-release and gun-firing circuits.

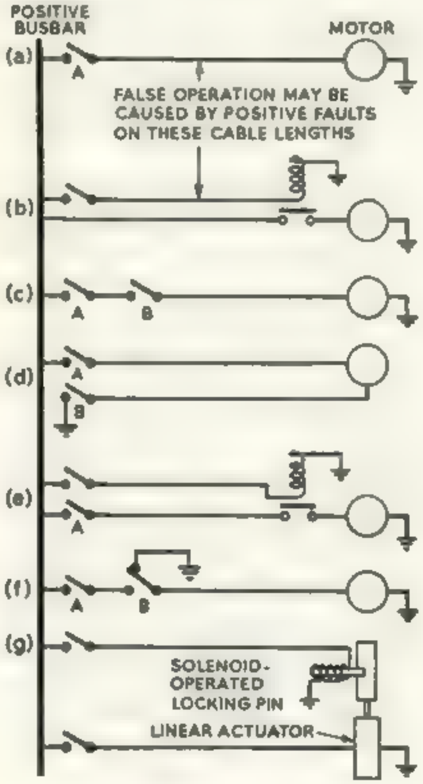


FIG. 10.51. *Some methods of preventing unintentional and accidental operation of loads.*

Fig. 10.51 (*a*) represents a motor which may be unintentionally operated by the closing of a switch, *A*. It would also operate in the event of a fault to live metal, a positive fault, on the line between the switch and the motor. Since the switch and the motor may be situated almost at opposite extremities of an aircraft, the probability of such a fault is not negligible. It should be noted that the fault potential is not reduced if the motor is controlled by a contactor, as shown in (*b*), since the line to the contactor coil is equally vulnerable.

Some safeguard against unintentional operation can be achieved by the use of mechanical safety catches built on to the operating switch. Duplication of the switch, as shown in (*c*), also reduces the probability of accidental operation but not of fault liability since the second switch, *B*, must be located near the first, *A*. Switch duplication can be made effective against fault operation if the second switch is in the negative line, as shown in (*d*). This is often not practicable owing to the additional length of cable which is required if the two switches are to be in close proximity. An alternative is to replace the second switch with a contactor situated close to the motor terminals, as shown in (*e*). In this case, positive faults on both the contactor and motor lines are necessary to cause false operation. A somewhat different arrangement, referred to as "back-contact earthing", is shown in (*f*). This uses only simple switches and is effective, provided the resistance from a positive fault to earth via the switch *B* is not high enough to cause significant current flow through the load.

A method which offers security against both electrical and mechanical failures is shown in (*g*). This requires extra equipment of a slightly more complex nature than the schemes previously described. All methods suffer from the disadvantage that normal operation depends on the functioning of extra components and the probability of failure is therefore increased. Metal-braided cable is sometimes used as a precaution against positive faults.

GROUND POWER SUPPLIES

It is not uncommon to depend solely on the use of polarized connectors (see Fig. 10.17) to ensure that a ground supply is correctly connected to the aircraft, but it is desirable also to check the supply. In the d.c. case, voltage and polarity should be checked, but often only the latter check is made. This is conveniently done with a polarized relay which, on operating, disconnects all aircraft power sources from the system and subsequently connects the ground power supply. Over-riding switches are sometimes required to enable the aircraft accumulator to be charged, *in situ*, from the ground supply and to enable the aircraft generators to be loaded externally for checking. A.C. ground supplies should be checked for voltage, frequency and phase sequence.

CHAPTER 11

Power Systems

EARLIER chapters have dealt with the component parts of systems and this chapter is intended to introduce the ways in which complete systems operate. The three principal types of systems, Direct-current, Constant-frequency Alternating-current, and Rectified Alternating-current, are considered separately. In Ref. 21 an attempt is made to indicate the considerations leading to the choice of a system and to discuss the advantages and peculiarities of each system. In practice the technical comparison of systems is relieved by strong personalities advocating their preferred systems and carrying on friendly feuds, the echoes of which may be detected in otherwise staid engineering journals and dignified lecture halls. It is certain, however, that no system stands clearly as the best system for all kinds of aircraft, and even for one type of aircraft it is often difficult to show that any one system is significantly better than others. Availability of equipment, previous experience and customers' preferences have influenced the manufacturers probably as much as the technical differences.

DIRECT-CURRENT SYSTEMS

Introduction. Before 1914 nearly all aircraft installations were d.c., and in aeroplanes, where power requirements were smaller than in airships and flight durations were shorter, primary or secondary batteries alone were commonly used. Some of the earliest d.c. generators were designed to provide "high-tension" and "low-tension" supplies for radio and were specifically part of the radio equipment and not a general-purpose electrical system. In other cases a secondary battery was charged by the low-voltage output and the low-voltage system thus formed was used to power equipment other than radio. These systems generally operated at about 12 volts, which became an accepted standard for much of the inter-war period, but systems using 24-volt lead-acid accumulators were introduced for the larger power systems in the 1930's. At present this is still a standard primary system for small aircraft and there is probably no aircraft which does not use 28 volts as either a main or subsidiary system voltage. The rapid growth of power requirements

during the second world war, and the continued subsequent growth, have led to the acceptance of 112 volts as a new system standard.

The term "24-volt system" is commonly used to describe the lower-voltage system but "28-volt system" is preferred. Both terms are understood to define a system using a battery of 12 lead-acid cells, in parallel with one or more generators, and the ambiguity arises because the actual system voltage varies considerably with the mode of operation. When the generators are not operating, the accumulator voltage is little more than 24 volts and can be much less if the accumulator is supplying a heavy load. When the generators are operating and supplying both the load current and a small charging current, the system voltage is rather more than 28 volts. The precise values depend on a number of variables such as accumulator temperature, internal resistance and state of charge, and the generator regulator characteristics and settings. A recent U.S.A. military specification allows a range of 25 to 29 volts under most flight conditions and a minimum of 17 volts during ground starting.

The higher-voltage system has been subject to minor variations. It is now generally accepted as the 112-volt system which, both in nominal voltage and number of lead-acid cells, is exactly four times greater than the 28-volt system. The minor variations have included systems using 54 cells (Ref. 14) and nominal voltages of 115 and 120 have been quoted.

CHOICE OF VOLTAGE

The reasons for the adoption of higher voltages as power requirements increased are several, but the most significant is the saving of cable weight. Table 11.1 gives data on cables to transmit power continuously over a distance of 30 ft. It shows that at 10 h.p. a 112-volt cable is only about 1/7th of the weight of a 28-volt cable. This saving is greater than would be expected from the current ratio alone, which is only 1 to 4. This discrepancy is explained under *Cable Ratings* in Chapter 10, and where Fig. 10.2 shows that a 267-amp. cable is about twice as heavy, per amp. carried, as one for 66·7 amp.

Table 11.1 also gives information on the volt drops and the power losses in the cables. Although the absolute values of the volt drops are less in the 28-volt system, when expressed as a fraction of the system voltage, they are greater. The allowable volt drop along a length of cable depends on the equipment to be supplied and it frequently happens in 28-volt systems, and where long cable runs are in use, that the size of cable installed must be greater than that required to carry the current without overheating.

The power loss in cables is always greater in 28-volt systems. This wasted power reflects on such things as the size and cooling of the generators, and the power demands on the main engines. Fortunately it is a distributed loss

and no particular difficulty is generally experienced in dissipating the heat. The most economic level for cable losses, taking into account their effects on other components of the system is discussed in Ref. 15. The authors deduce that little or no weight could be saved by accepting greater volt drops and losses in 112-volt systems, but that 28-volt systems are heavier than they would be if greater volt drops could be accepted. The information presented in the paper is extremely useful, even though it refers only to the generating systems and not to complete power systems. Reference is made to this paper primarily because it discusses the design of d.c. generating systems in greater detail than is practicable here.

Equipment for which 112 volts is less suitable than 28 volts is that which contains small relay or motor windings. At the higher voltage these consist of many turns of fine wire and are difficult to manufacture, particularly in a robust form. Similarly, filament lamps are more robust if designed for the lower voltage. The availability of 28-volt equipment is much greater than that of 112-volt equipment and this is an influential factor in the choice of system voltage. Likewise, the existence of ground equipment for servicing and checking 28-volt equipment, is a deterrent to change.

EARTHING

All present d.c. systems use the airframe as a return conductor connected to the negative terminal of the supply. Generally the resistance measured between any two points on the airframe is very low since, as explained under *Bonding and Earthing* in Chapter 10, this is a requirement for protection

Table 11.1

CABLE DATA

Horse-power	*Voltage*	*Current*	*Cable*		*Volt drop*		*Power loss (watts)*
			Weight (lb.)	*Resistance (ohms)*	*Volts*	*%*	
10	28	266·6	23·4	0·00158	0·422	1·5	112·4
	112	66·7	3·3	0·013	0·866	0·773	57·8
5	28	133	9·3	0·0042	0·57	2·0	76·0
	112	33	1·6	0·032	1·1	0·98	36·3
1	28	26·6	1·6	0·032	0·852	3·04	22·6
	112	6·7	0·26	0·3095	2·06	1·84	13·8

Cable weights, voltage drops and power losses for the transmission of various powers a distance of 30 ft. Earth return is assumed and the resistance of the return path is neglected.

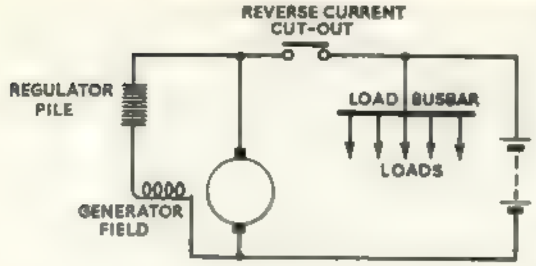


FIG. 11.1. *Power source circuit of a single-generator d.c. system.*

against lightning. The ability of the structure to carry large currents is also usually adequate but it is necessary to check that this is so for both normal and fault currents.

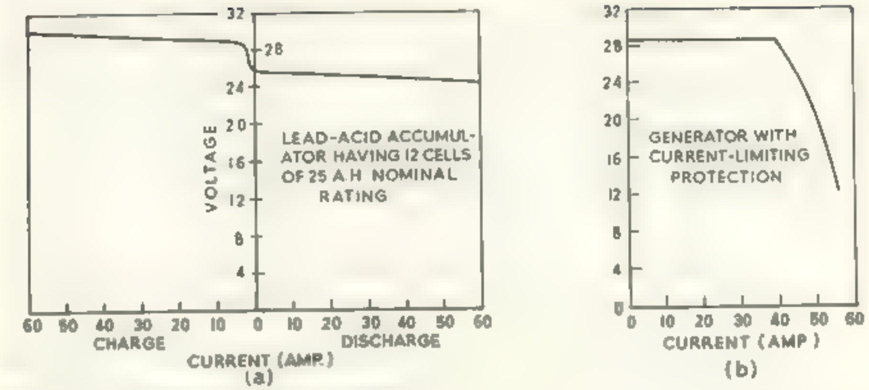
The use of the airframe can cause currents to follow circuits which are loops or turns of large cross-sectional area. Such currents give rise to extensive magnetic fields and, depending on the magnitude and nature of the current, these may interfere with the operation of some equipments. If the current is steady and free from ripple and high-frequency components, the effects of the current loop will probably be confined to instruments which depend for their operation on weak magnetic fields, such as the magnetic compass. If high-frequency components are present the effects may be extended to communication equipment. Such components, which typically arise from commutation, are normally filtered at their source. Difficulties caused by current loops can be overcome by providing a return cable positioned alongside the outgoing cable, thereby reducing the loop area to a minimum.

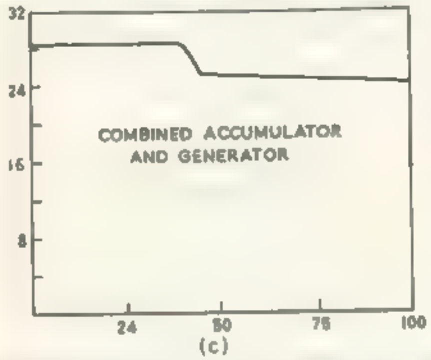
SINGLE-GENERATOR SYSTEMS

A single-generator d.c. system is illustrated in Fig. 11.1. Such systems were used extensively when power requirements were small but are now to be found only in small single-engined aircraft. Larger single-engined aircraft sometimes use two generators driven from the same engine.

Some aspects of the performance of a single-generator system may be deduced from the diagrams of Fig. 11.2. Diagram (*a*) shows a voltage/current characteristic for a typical lead-acid accumulator and diagram (*b*) a characteristic for a small generator fitted with a voltage regulator and current limiting protection, as described in Chapter 5 (see *Voltage Regulator*). By adding the current abscissae at several voltages the curve of Fig. 11.2 (*c*) is obtained which is the voltage/current characteristic for the generator and accumulator connected in parallel.

Fig. 11.2 (*d*) shows the characteristic of a shunt motor. By superimposing this load characteristic on the combined source characteristic (Fig. 11.2*c*) it may be seen from the point of intersection of the two curves, that the voltage at the motor terminals would be 28·5 volts. The same result is obtained if the





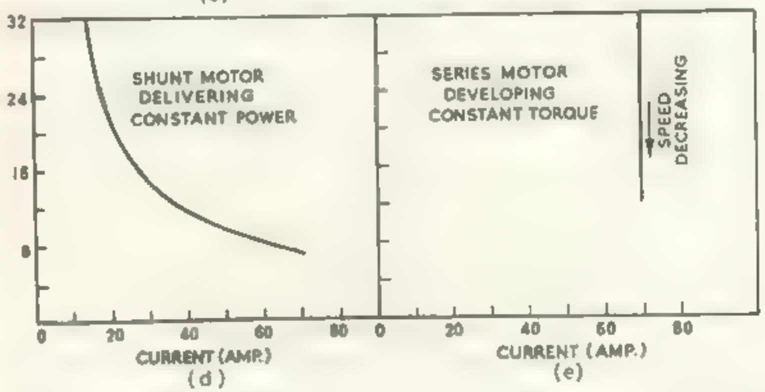


FIG. 11.2. *Voltage/current characteristics for simple power sources and loads (single-generator direct-current system).*

generator alone is considered as the source. In the event of a larger current demand, such as that represented by the series motor characteristic (Fig. 11.2*e*) the combined source delivers 70 amp. at 25 volts whereas the generator alone could not supply the load. The ability of the combined source to supply heavy loads of limited duration, even at reduced voltage, is very useful.

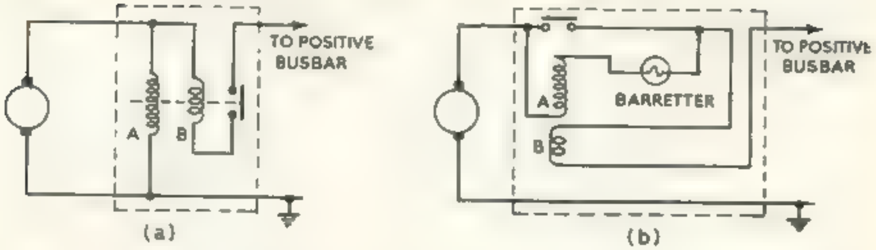


FIG. 11.3. *Circuits and connexions of* (a) *definite-voltage reverse-current cut-out;* (b) *differential-voltage reverse-current cut-out.*

Diagrams of the kind shown in Fig. 11.2 can be applied to more elaborate systems to deduce both steady-state and transient operating conditions. Although cumbersome, they are worth while because in most cases the shapes of the voltage/current characteristics are not easily described mathematically. An account of the derivation and application of these curves is given in Ref. 16.

In modern systems generators are invariably capable of providing all the power demanded by the heaviest short-duration loads without any significant reduction of system voltage. This is a convenient, though incidental, consequence of installing large generators, since the sensitivity of some of the equipment installed in modern aircraft is such that system voltage reductions of this kind are not normally tolerable.

From Fig. 11.2 (*a*) it may also be deduced that in the event of the generator operating at abnormal voltage, the accumulator will accept a higher than normal charge current, thereby loading the generator and restraining the system voltage. In a system having a large accumulator and small generator this is very effective; even in modern systems with large generators and a relatively small accumulator it is still useful.

REVERSE-CURRENT CUT-OUTS

Fig. 11.1 shows a reverse-current cut-out (R.C.C.O.) between the generator and the accumulator. This item is a feature of all d.c. systems. Its primary function is to connect the generator to the load busbars whenever it is capable of supplying power, and to disconnect it whenever it ceases to be capable of supplying power.

Two types have been used, the definite-voltage and the differential-voltage types. The essential circuits of both types are shown in Fig. 11.3. The definite-voltage cut-out is not polarized by a permanent magnet but is held in the open position by a spring. Coil *A* (Fig. 11.3*a*) sets up an m.m.f. which tends to close the cut-out and the mechanism is adjusted so that it closes when the generator output voltage is equal to the system voltage. The

m.m.f. of coil *B* assists that of coil *A* if current flows from the generator to the system. The cut-out opens when the combined m.m.f. falls below a critical value as a result of reverse current flow or low generator voltage.

In multi-generator systems the adjustment of the relay is fairly critical. If adjusted to close at too low a generator voltage, the flow of reverse current occurring when the contacts close immediately opens the cut-out. Such an adjustment causes the cut-out to "chatter". If adjusted to close at a voltage substantially higher than the system voltage the system experiences a voltage surge and reverse current may flow in other generators. Precise and similar adjustment is therefore required for all cut-outs in a system and this has proved to be difficult to achieve and maintain. Since the cut-out is not polarized it can be held closed by excessive reversed current flow.

The differential-voltage cut-out (Fig. 11.3*b*) was introduced mainly because of the difficulties of using the definite-voltage type in multi-generator systems. It is polarized by a permanent magnet such that, when the generator voltage exceeds the system voltage by about 0·5 volt, the m.m.f. of coil *A* closes the cut-out. Reverse generator voltage cannot close the cut-out because the m.m.f. of coil *A* is small compared with the biasing m.m.f. of the permanent magnet. Coil *B*, as in the previous type, keeps the cut-out closed while forward current is flowing but in this type it is not assisted by coil *A*, which is short-circuited as soon as the contacts close.

Coil *A* is required to operate at only 0·5 volt but can be subjected to full system voltage, for example, before the generator is excited. It therefore requires a current-limiting device which in the simplest cut-outs is a barretter lamp. These lamps tend to limit the current because they are constructed with tungsten filaments which have a positive temperature coefficient.

Differential-voltage cut-outs operate when the generator voltage exceeds the system voltage. This is satisfactory for the first generator to be connected to the system, since its regulated voltage is substantially higher than the accumulator voltage, but not for the second and subsequent generators. To enable the second generator cut-out to operate, the generator regulator must be momentarily adjusted to give a voltage slightly higher than normal. This is achieved in some systems by inserting a resistor in series with the generator regulator sensing coil to give about 10 per cent excess voltage. The resistor is short-circuited by auxiliary contacts on the differential cut-out when it closes. As before, the cut-out is held closed by the m.m.f. of the series coil *B*.

Some further elaboration of cut-outs is often necessary. In order to enable the relay element to be made sensitive the relay contacts may be used to operate a contactor instead of opening the generator circuit. This permits smaller and lighter contacts to be used, since they carry only a small current, and the operating force required from the relay is much smaller. The

"cut-out" then consists of two distinct components, a relay of the differential or definite-voltage type, usually the former, and a contactor.

The differential cut-out, as shown in Fig. 11.3 (*b*) would continuously discharge the system accumulator. Thus an isolating switch is required. An alternative is to use an under-voltage relay instead of a barretter lamp, the relay being arranged to close the differential coil circuit when the generated voltage reaches about 70 per cent of the system voltage.

Differential relays have been used to perform the following auxiliary functions on closing, in addition to operating the cut-out contactor; (*a*) to switch off the power failure warning lamp; (*b*) to connect the equalizing circuit; (*c*) to short-circuit the "voltage-raising resistor", previously mentioned; (*d*) to close interlocks preventing large rotary convertors from being operated from the system accumulator.

CO-ORDINATION OF THE R.C.C.O. AND R.C.C.B.

It was explained in Chapter 10 (see *Generator to Busbar*) that co-ordination is necessary between these components both to avoid the R.C.C.O. contactor assuming the duty of a circuit-breaker and to avoid sound generators being disconnected from the system in the event of an over-voltage fault.

The maximum reverse current which can occur during an over-voltage fault is as much as several times the full-load current of a generator, the value depending mostly on the generator characteristics, and this is the maximum current which the R.C.C.O. contactor need be designed to break. It is also the highest current at which the R.C.C.O. should operate before the R.C.C.B. At higher currents the R.C.C.B. should operate before the R.C.C.O., and as quickly as possible, both to isolate the fault quickly and to prevent damage

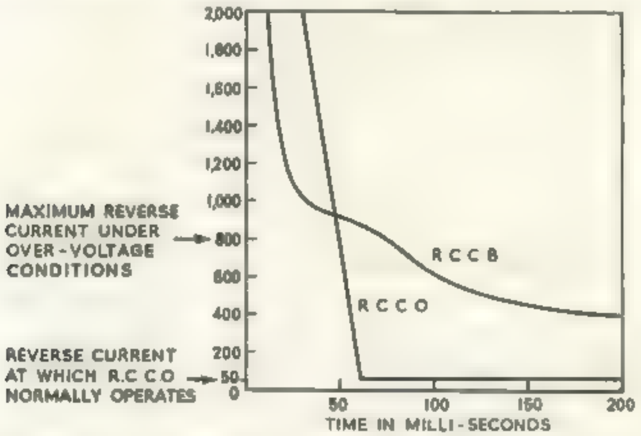


FIG. 11.4. *Illustrating co-ordination between the R.C.C.O. and R.C.C.B. in d.c. systems, and showing the maximum reverse current in amperes.*

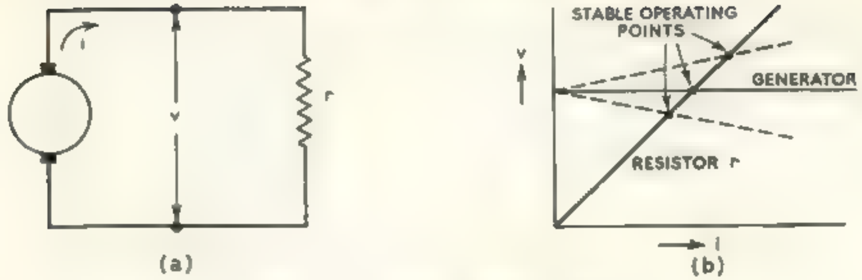


FIG. 11.5. *A circuit which is stable.*

to the R.C.C.O. contactor contacts. At all lower currents the R.C.C.O. should operate first. These requirements have led to the development of R.C.C.B.'s for this particular duty, which have irregular time/current characteristics as shown in Fig. 11.4.

PARALLEL OPERATION OF GENERATORS

Stability. An example of a stable circuit is shown in Fig. 11.5 (*a*) and the voltage/current curves for the two components in Fig. 11.5 (*b*). The circuit is called stable because no momentary disturbance of the generator drive or changes of the component values or settings would cause a permanent change in the operating conditions. Provided the voltage/current characteristics are plotted in the manner shown, it may be taken as a criterion of stability that

$$\frac{dv}{di_{\text{load}}} \text{ is greater than } \frac{dv}{di_{\text{power source}}}$$

or expressed in words, that the slope of the voltage/current characteristic of the load is greater than the slope of the power source—in this case, generator characteristic. The broken-line voltage-current curves represent generators having both rising and falling characteristics, and it may be seen that with the load being considered these are also stable. It would be possible to have a generator with a voltage/current characteristic rising, initially, at a greater rate than the curve for the load resistor, as shown in Fig. 11.6. This could be achieved by having a generator with a large series field winding and a low value of load resistance. Such an arrangement would, however, have a stable operating point, because all generator characteristics turn over at some value

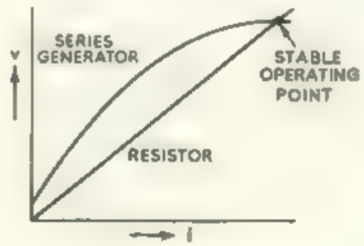


FIG. 11.6. *Stable operation of a series-wound generator with resistive load.*

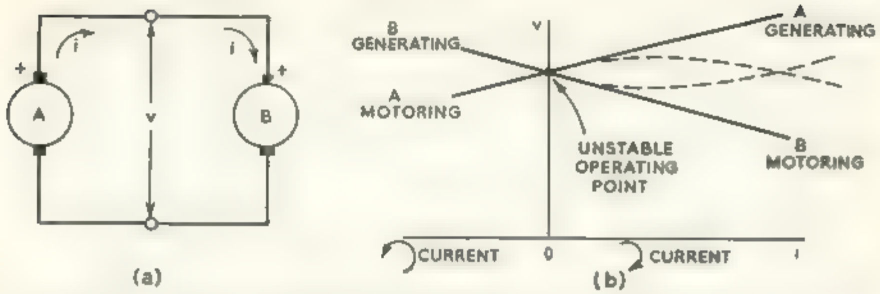


FIG. 11.7. *Illustrating an unstable circuit of two generators in parallel, and showing the voltage/current curves.*

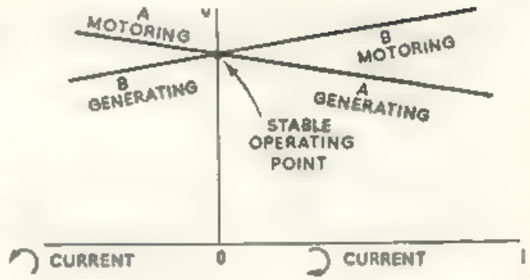
of current for such a reason as magnetic saturation of the iron. The operating point would almost certainly represent an overloaded condition for the generator.

Remembering the simple criterion for stability, consider two generators in parallel as shown in Fig. 11.7 (*a*). It is possible for generator *B* to function as a load for generator *A*, or vice versa, if the generators are capable of receiving current, that is, of operating as motors. If current circulates as shown, then generator *A* is supplying power to generator *B*. The voltage, current curves for generators with rising characteristics, speed being assumed constant, are shown in Fig. 11.7 (*b*). The slope of the load curve, generator *B*, is negative and therefore less than that of the generator; thus the circuit is unstable within the normal ratings of the machines.

The operating condition for this circuit is given by the intersection of the two curves; it is ideally positioned in that no current circulates between the two machines. However, a slight departure from this condition, such as could not be avoided in practice, causes a circulating current which tends to increase and would probably reach a value much in excess of the safe current for the machines. Even if the currents were restricted to a safe value, which might be the case if the voltage/current curves were non-linear as shown by the broken-line curves in Fig. 11.7 (*b*), the circulating current is still undesirable because of the heating of the machines. In a practical system the reverse-current cut-out of generator *B* would operate, probably chattering continuously, and the system would be unserviceable.

Referring again to the full-line curves of Fig. 11.7 (*b*), a change of no-load voltage of one of the machines moves the operating point to a condition where current circulates but the system is still unstable. Stability in this simple system can be achieved only by changing the generating characteristics from rising to falling as shown in Fig. 11.8. A system stabilized in this way is inherently stable but has the disadvantage that the system voltage decreases

FIG. 11.8. *Stable condition of two generators in parallel.*



as the system is loaded. This may be avoided by more elaborate arrangements which are discussed later (see *Master Regulator Constant-voltage Method*).

LOAD SHARING

It is required that generators of an aircraft system share the load equally. This criterion is not the most economical one for operating a power system and is not generally adopted in industrial systems. It is, however, universally preferred for aircraft for the following reasons.

(*a*) Continuity of the power supply in the event of the loss of any generator or its drive.

(*b*) Maximum system capacity is available only if all generators deliver full output in parallel. This condition is most readily achieved if the system is designed so that generators share the load, from zero to maximum, equally.

(*c*) The large system capacity obtained by operating all generators in parallel, enables peak loads to be supplied with minimum effect on the system voltage. It is also necessary for clearing some kinds of system faults.

(*d*) Generator reliability and life is probably enhanced by operating at the relatively moderate temperatures occurring at part load.

METHODS OF OBTAINING STABLE PARALLEL OPERATION AND EQUAL LOAD SHARING

Generators with Series Resistors. A simplified diagram of such a system is shown in Fig. 11.9. The voltage regulators are assumed to be perfect and to maintain the generator terminal voltages constant at all values of load current. Falling voltage/current characteristics are secured by connecting

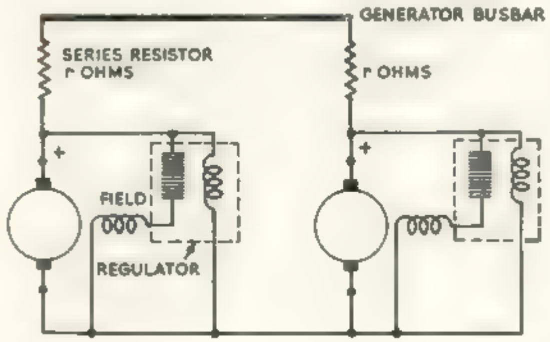


FIG. 11.9. *Paralleled generators using the voltage-droop method of stabilizing and load sharing.*

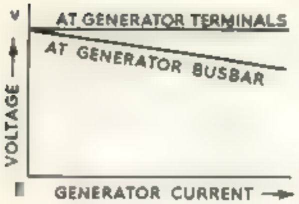


FIG. 11.10. *Voltage/current characteristic for the generator circuits of Fig. 11.9.*

resistors between the individual generators and the generator busbar. This is sometimes known as the voltage-droop method.

The system is stable because the voltage/current characteristics of the generators, together with their series resistors, are falling, as shown in Fig. 11.10. Exact load sharing at all values of system load can also be obtained if (*a*) the regulator characteristics are identical; (*b*) the resistances of series resistors and cables together, are equal; and (*c*) the no-load voltages are equal.

These simple conditions are difficult to achieve practically. Regulator characteristics differ considerably and change with temperature and time. The series resistors must be small if the fall in system voltage with load is not to be excessive, and their resistances may be comparable with those of the generator cables. Since the cables are usually of different lengths for outboard and inboard generators, and since they are often carried in regions of different temperature, it is difficult to ensure that they are of equal resistance at all times. The effect of contact resistances at cable terminations is also significant. The no-load voltages depend very much on the regulator. Thus this simple system is stable but does not readily give good load sharing.

In order to study the effectiveness of the load sharing system it is necessary to define unbalance current. This is defined here as the difference between the current of *any one* generator and the average current of *all* the generators. Alternative definitions have been used but this is preferred because it gives the value by which the current of any generator differs from the ideal value. Table 11.2 gives examples of unbalance current using this definition.

It is also necessary to define generator error voltage. Here, generator error voltage in a system of n generators is defined as the difference between the generator terminal voltage at $1/n$th of the total system load (the load-sharing circuit being inoperative), and the on-load system voltage. Other definitions are in use but this is preferred because unbalance current, as previously defined, when expressed in terms of this error voltage, is independent of the number of generators in the system.

Operation of a Multi-generator System. Fig. 11.11 (*a*) indicates how a load is shared by two generators having constant-voltage regulators and identical series resistors. The broken-line voltage/current characteristics indicate how the load is shared if No. 1 generator is set to give a higher no-load voltage than No. 2, the two voltages being such that the system

Table 11.2

EXAMPLES OF UNBALANCE CURRENT

Total load current (Amp.)	Generator Currents				Unbalance currents			
	1	2	3	4	1	2	3	4
i	i_1	i_2	i_3	i_4	i_{u1}	i_{u2}	i_{u3}	i_{u4}
400	100	100	100	100	0	0	0	0
400	130	90	90	90	30	−10	−10	−10
200	20	60	60	60	−30	10	10	10
200	150	50	*	*	50	50	*	*
300	166	67	67	*	66	33	33	*
400	175	75	75	75	75	25	−25	25

* signifies: generator inoperative.

$i_{u1} = i_1 - (i_1 + i_2 + i_3 + i_4)/4 = i_1 - i/4.$

voltage is unchanged. No. 1 delivers more current than No. 2 and the unbalance currents are represented by BC and $-BC$ respectively. The magnitudes of these unbalance currents in relation to the voltage errors may be deduced from the diagram.

The ratio $\frac{BA}{BC}$ is the slope of the voltage/current characteristic of No. 1 generator which is numerically equal to the value of the series resistor, r: BA is the voltage error of No. 1 generator, δv_1, and BC is the unbalance current, i_{u1}.

$$\left.\begin{aligned} &\text{Thus,}\quad \frac{\delta v_1}{i_{u1}} = r \text{ and } i_{u1} = \frac{\delta v_1}{r} \\ &\text{Similarly}\quad \frac{\delta v_2}{i_{u2}} = r \text{ and } i_{u2} = \frac{\delta v_2}{r} \end{aligned}\right\} \qquad (1)$$

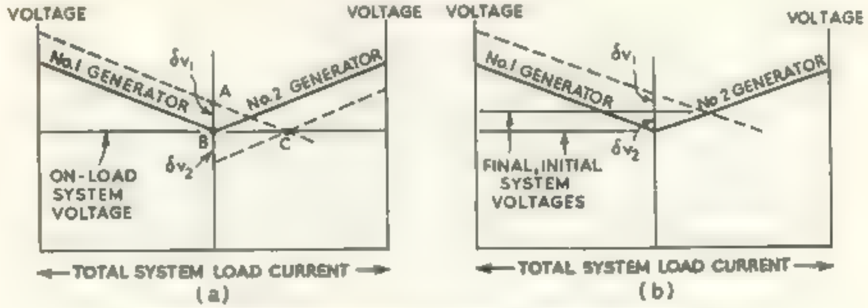


FIG. 11.11. *Load-sharing conditions for the circuit of Fig. 11.9.*

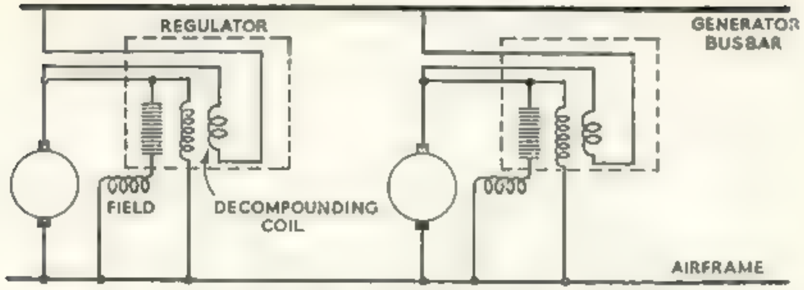


FIG. 11.12. *Paralleled generators using regulator decompounding coils.*

Since δv_2 is equal to $-\delta v_1$, i_{u2} is also given by $-\frac{\delta v_1}{r}$. In this example the system voltage was unchanged and the errors δv_1 and δv_2 measured, as defined, with respect to the system voltage, are equal to the errors measured with respect to the original generator voltages. Fig. 11.11 (*b*) illustrates the case where No. 1 generator voltage only is changed and it is shown that δv_1, as defined, is only half the actual change of generator voltage because the system voltage is also increased. For a system of n generators equations (1) still apply, the unbalance current for the nth generator being given by:

$$i_{un} = \frac{\delta v_n}{r} \tag{2}$$

If it is assumed that only one generator, say No. 1, is incorrectly adjusted and that the remainder deliver equal currents, then

$$i_{u2} \text{ to } i_{un} = \frac{-\delta v_1}{(n-1)\times r} \tag{3}$$

since δv_2 to $\delta v_n = \frac{-\delta v_1}{(n-1)}$.

Applying equations (2) and (3) to a system of four generators in which δv_1 is 0·5 volt, $v_2 = v_3 = v_4$ and r is 0·01 ohm, $i_{u1} = \frac{0{\cdot}5}{0{\cdot}01} = 50$ amp., and $i_{u2} = i_{u3} = i_{u4} = \frac{-0{\cdot}5}{(4-1)\times 0{\cdot}01} = -16{\cdot}7$ amp.

The value of r chosen for this example, 0·01 ohm, would be practical for generators of 28 volts, 200 amp. rating; the fall of system voltage between no-load and full load would be 2 volts. The error voltage, δv_1 of 0·5 volt, is also realistic, being a little less than 2 per cent of the nominal voltage. The unbalance currents are, however, barely tolerable since when No. 1 generator is fully loaded the others are delivering only 200—(50+16·7)=133·3 amp. The maximum system capacity, limited by the condition that No. 1 generator shall not be overloaded, is therefore only 600 instead of 800 amp. A higher

value of r would give better load sharing but a system drop of more than 2 volts at full load would not generally be acceptable.

In practice, such systems have been trimmed at fairly frequent intervals while in operation. Although this is a trivial electrical adjustment it is necessary to have all the main engines running, and is likely to be prolonged while regulators warm up and settle, so that it is a considerable embarrassment to operators.

Series Resistors. The fitting of these simple components to a system is not to be taken lightly. The power wasted in heat in each resistor of the example is 400 watts, 7½ per cent of each generator output. Some ventilation is necessary to remove this heat. Attention is also necessary to ensure that the resistors are safe from accidental contact; this is equally true for resistors connected in the positive cable, as shown in Fig. 11.9, and in the negative cable, as shown in Fig. 11.14. The weight of each resistor, complete with mountings and terminals, is likely to be about 2 lb. One minor compensation is that the resistor, or a part of it, can be used as an ammeter shunt.

GENERATORS WITH REGULATOR DECOMPOUNDING COILS

A circuit diagram of a system using regulator decompounding coils is shown in Fig. 11.12. This is also a droop method of obtaining stability and load sharing. It operates in the same way as the previous method but the series resistor and its associated losses are eliminated. One disadvantage of this method is that the regulator must be connected in the generator cable. This may not always be convenient since it is preferable to mount the regulator in a position where it is readily adjusted and can be protected from the more severe environmental conditions. Diversions of the generator cable, which weighs about ½ lb. per ft., are undesirable. As with the series resistor droop method, the system voltage falls with load and precise load sharing requires a high rate of fall.

MASTER REGULATOR CONSTANT-VOLTAGE METHOD

This method was introduced in British multi-generator systems during the second world war. Individual generators of the system have falling voltage/current characteristics, obtained by using regulator decompounding coils, and the system voltage is controlled to a constant value by a single master regulator which operates simultaneously on the voltage-sensing coils of all the generator regulators. Unlike the generator regulators, the master regulator is arranged to offer a reduced pile resistance when the system voltage is high. Under these conditions the currents in the generator regulator voltage-sensing coils are all increased simultaneously and the system voltage is reduced. This method is capable of much better load sharing than those previously described because it is possible to make the slopes of the

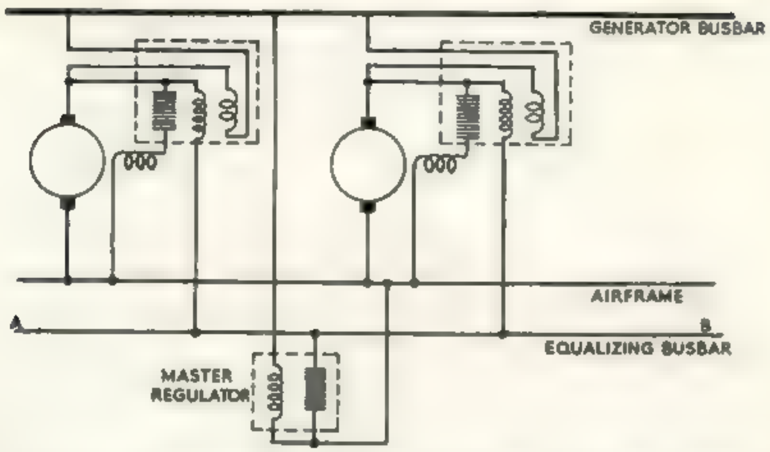


FIG. 11.13. *Constant-voltage d.c. system controlled by a master regulator.*

individual voltage/current characteristics much greater. A 25-per cent volt drop at full load is a typical value instead of about $7\frac{1}{2}$ per cent. The system voltage, however, can be controlled by the master regulator to within about 2 per cent of the nominal value.

In common with all methods of parallel operation which give stability, good load sharing and constant system voltage, this method has one feature which requires particular attention. This is a circuit which interconnects all the individual generator regulators. In the event of this circuit being faulted, whether by open-circuits or by connexion to earth or a positive line, all the generators are affected and the entire power supply is jeopardized.

A circuit diagram for this method is given in Fig. 11.13. The interconnecting circuit is identified as the "equalizing busbar" although it is usually a cable rather than a busbar. Immunity against one open-circuit fault is secured by connecting the ends of the "busbar", *A* and *B* in Fig. 11.13, to form a loop. This is generally done and the busbar is then called an equalizing loop.

REGULATOR EQUALIZING COIL, CONSTANT-VOLTAGE METHOD

All the methods previously described have depended on the falling voltage/current characteristics of individual generators to give stability. This method depends on a system of equalizing in which the errors in load sharing provide correcting signals to the generator regulators. It was introduced on U.S.A. aircraft during the second world war and has subsequently been generally preferred to the British master regulator method. The circuit of a system using this method is shown in Fig. 11.14. With the aid of this circuit it is proposed to deduce an expression for unbalance current in terms of the

more important circuit resistances, a regulator constant k, and the error voltage. The definition of unbalance current, i_u, given on page 252 also applies here. Hence, for a four-generator system,

$$i_{u_1}=i_1-\frac{i_1+i_2+i_3+i_4}{4}$$

where the currents are as indicated in Fig. 11.14.

Let the potential of the equalizing busbar be v_{eq} volts with respect to the airframe. Consideration of the circuit will show that this is a negative potential but this does not affect the argument. Then the current, i_{e_1}, through the equalizing coil of No. 1 generator is given by:

$$i_{e_1}=\frac{v_{eq}-v_{er_1}}{r_c} \tag{4}$$

where v_{er_1} is the potential of the live terminal of the equalizing resistor of No. 1 generator measured with respect to the airframe.

Similarly, $$i_{e_2}=\frac{v_{eq}-v_{er_2}}{r_c} \text{ etc.,} \tag{4a}$$

where suffixes 2, 3, and 4 refer respectively to generators 2, 3, and 4.

Summing the currents flowing to point *P*, Fig. 11.14,

$$i_{e_1}+i_{e_2}+i_{e_3}+i_{e_4}=0 \tag{5}$$

Substituting for these currents from equations (4) and (4a),

$$\frac{v_{eq}-v_{er_1}}{r_c}+\frac{v_{eq}-v_{er_2}}{r_c}+\frac{v_{eq}-v_{er_3}}{r_c}+\frac{v_{eq}-v_{er_4}}{r_c}=0$$

Multiplying by r_c and rearranging,

$$v_{eq}=\frac{v_{er_1}+v_{er_2}+v_{er_3}+v_{er_4}}{4}$$

Substituting for v_{eq} in equation (4) for i_{e_1},

$$i_{e_1}=\frac{1}{r_c}\left(\frac{v_{er_1}+v_{er_2}+v_{er_3}+v_{er_4}}{4}-v_{er_1}\right) \tag{6}$$

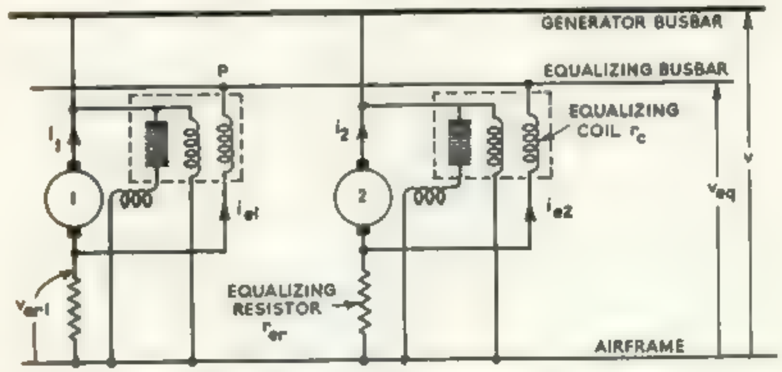


FIG. 11.14. *Constant-voltage d.c. system using regulators with equalizing coils.*

Now, $v_{er1}=(i_1+i_{e1})r_{er}$
where r_{er} is the resistance of the equalizing resistors.

Similarly, $v_{er2}=(i_2+i_{e2})r_{er}$ etc.

Substituting in equation (6),

$$i_{e1}=\frac{r_{er}}{r_c}\left\{\frac{i_1+i_2+i_3+i_4}{4}+\frac{i_{e1}+i_{e2}+i_{e3}+i_{e4}}{4}-i_1-i_{e1}\right\}$$

$$=\frac{r_{er}}{r_c}\left\{\frac{i_1+i_2+i_3+i_4}{4}-i_1-i_{e1}\right\}$$

since $i_{e1}+i_{e2}+i_{e3}+i_{e4}=0$, equation (5)

$$=\frac{r_{er}}{r_c}\left\{(-i_{u1})-i_{e1}\right\}$$ since, by definition,

$$i_{u1}=i_1-\frac{i_1+i_2+i_3+i_4}{4}.$$

Rearranging, $$i_{u1}=-i_{e1}\frac{r_c+r_{er}}{r_{er}} \tag{7}$$

Now i_e, flowing through the equalizing coil of a regulator, causes a change of generator terminal voltage δv.

Let $$\frac{\delta v}{i_e}=k, \tag{8}$$

a constant dependent on the design of the equalizing coil and regulator. A practical value is about 10. Since all generators are connected to a common busbar, the resistance of which may be neglected, their terminal voltages are equal at some value v. For each generator this voltage may be considered to be made up of two increments, v_1 and δv_1, in the case of generator No. 1, where δv_1 is attributable to the equalizing coil current i_{e1}. Thus, $v_1+\delta v_1=v$.

Substituting for δv_1 from equation (8); $v_1+k\times i_{e1}=v$.

Hence, $i_{e1}=\frac{v-v_1}{k}$.

Substituting in equation (7) for i_{e1},

$$i_{u1}=\frac{v_1-v}{k}\times\frac{r_c+r_{er}}{r_{er}} \tag{9}$$

The term (v_1-v) is the previously defined error voltage, the difference between generator terminal voltage at $1/n$th of the total system load and the system voltage; v_1 would, of course, be determined with zero current through the equalizing coil. It is assumed that the regulator maintains constant generator voltage, v_1, at all loads but if this is not so, since the equalizing system tends to ensure that each generator delivers $1/n$th of the total load (v_1-v) is still approximately equal to the defined error voltage.

The value of unbalance current for a particular error voltage can be minimized by designing for a high value of k. Unfortunately, this causes instability, particularly during conditions of changing load or generator

speed. The resistance r_c should, strictly, be defined to include the resistances of the leads from the equalizing coil to the equalizing busbar and resistor. The resistance of the equalizing coil itself can be reduced by decreasing the number of turns, but this would reduce k, or by increasing the size of the regulator and using a heavier gauge wire. The resistance of the equalizing resistor, r_{eq}, can be advantageously increased provided it is small compared with r_c. A practical value for r_{eq} is about 0·0025 ohm whereas r_c is likely to be about one ohm. Thus it is generally possible to improve load sharing by increasing r_{eq} but the disadvantages associated with large series resistors make this course undesirable. It should be noted that the series resistors of this system do not cause the system voltage to fall with increasing load because the voltage regulator sensing coils are connected across both the generators and their resistors. Modern generators use the resistances of their interpole, compensating and series windings as part of the equalizing resistance.

Assuming a voltage error of 0·5 volt and the suggested values for the constants, equation (9) gives the unbalance current as

$$i_u=\frac{0{\cdot}5}{10}\times\frac{1+0{\cdot}0025}{0{\cdot}0025}=20{\cdot}05 \text{ amp.}$$

This is less than half the unbalance current calculated for the voltage droop system in which the series resistors were four times greater.

The number of generators in a system affects the values of unbalance currents regardless of the method of load sharing. This may not be apparent from the expressions for unbalance currents but further consideration will show that the error voltage (v_1-v) is, itself, dependent on the number of generators. In the two-generator system using the voltage droop method, Fig. 11.11 (*b*) shows that the error voltage is only half the change of No. 1 generator voltage. If the same change is made in a system of n generators, all of which are identical in voltage settings and characteristics, the error voltage of the changed generator would be equal to the change multiplied by $(n-1)/n$. Error voltages of the other generators would be equal to the change multiplied by $-1/n$. Systems having a large number of generators therefore allow the largest unbalance current in the generator with the changed setting, and the smallest change of system voltage.

EQUALIZING CIRCUITS

It was noted earlier (see *Master Regulator Constant-voltage Method*) that a circuit, common to all generators, is a characteristic feature of all constant-voltage methods of load sharing, and that this circuit is critical because if faulted it endangers the entire system. Consideration of the equalizing-coil method will show that there is a further danger to be avoided which arises when one generator operates at abnormally high or low voltage. In this

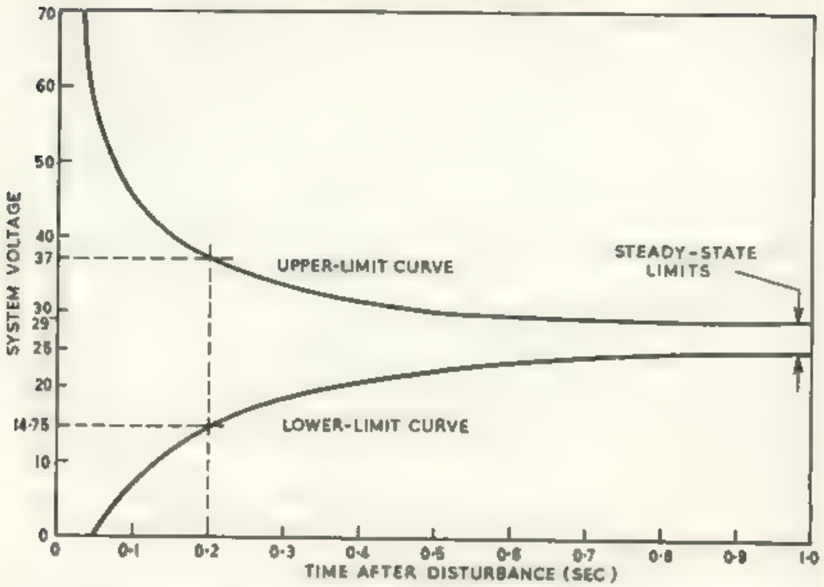


FIG. 11.15. *A method of specifying system voltage limits under transient conditions.*

event the equalizing circuit functions, as it normally does, to make all generators deliver equal currents, and will tend to raise or lower the system voltage towards that of the faulted generator. It is inevitable that a circuit giving the best load sharing under normal conditions will be most sensitive to such a fault and, since good load sharing is necessary, this undesirable effect is experienced and is avoided by disconnecting the load-sharing circuit of the faulty generator from the equalizing busbar. In the case of over-voltage this is initiated by the over-voltage protection circuit, described in Chapter 10 (see *Generator to Busbar*), and in the case of under-voltage by the reverse-current relay, described in this chapter under *Reverse-current Cut-outs.*

SPECIFICATION OF A DIRECT-CURRENT POWER SUPPLY

The details of such a specification will depend on the type of aircraft and the service for which it is to be used but the principal quantities to be specified are: (1) the system voltage with upper and lower limits under the several different operating conditions, such as take-off, cruise, emergency, etc.; (2) the power required; (3) the acceptable degree of ripple or noise; (4) the reserve generating capacity; (5) the fault immunity of the system.

The specification of system voltage is necessary, not only under steady conditions, but also for the time immediately following a normal disturbance, such as bringing a generator or load on to the system. The method

adopted by the U.S.A. Services is indicated in Fig. 11.15. As an example to illustrate the interpretation of the chart, the curves specify that at 0·2 second after the occurrence of a disturbance the acceptable instantaneous voltage limits, between which the system voltage should lie, are 14·75 and 37 volts. At times later than 1·0 second the normal steady-state limits apply. Different curves may be used to specify the voltage limits under the different operating conditions. The U.S.A. Military Specification (Ref. 18) gives special lower-limit curves for ground start and emergency conditions. The power required may be conveniently specified by preparing a table indicating each individual load and the times when they are operated. Part of such a table is given as Table 11.3. Further, more detailed examples are to be found in British Civil Airworthiness Requirements, Ref. 13.

Noise or superimposed ripple at radio frequencies is generally intolerable owing to interference with communication equipment but ripple at lower frequencies may sometimes be present without serious effects. The magnitude of such ripple can be estimated with a high-impedance a.c.-reading valve voltmeter. A peak-to-peak value of up to 10 per cent of the nominal system voltage may be acceptable. It is noticeable that, as equipments become more refined, the effects of ripple and irregularities in the supply are increasingly apparent and it is to be expected that future power supply specifications will be more detailed in this respect.

Civil aircraft systems are often designed so that the loss of one generator does not necessitate the shedding of any essential loads or passenger comfort loads. Military aircraft, in which the loss of generators or their drives is an anticipated hazard, are frequently required to be able to maintain all services essential for combat or completion of a mission with only half the installed generators operating. The continual growth of electrical loads has, however, frequently forced departures from these ideals.

Although it is not possible to specify precisely a degree of fault immunity for a system, it is practicable to specify generally in such terms as these; that any single fault shall be incapable of rendering the entire system inoperative or of causing serious damage to the aircraft structure, and, that short-circuit faults on individual load circuits shall be cleared without interruption of the supply to any other circuits. The extreme limits of over-voltage can be specified by an upper-limit curve similar to the upper-limit curve shown in Fig. 11.15. It can also be specified that critical circuits such as generator excitation and protective circuits shall be provided with a power supply independent of that which they serve.

LARGE FOUR-GENERATOR SYSTEM

A diagram of a hypothetical system for a large four-engined aircraft is shown in Fig. 11.16. The four generators each have an output of 30 kW at

Table 11.3

METHOD OF TABULATING SYSTEM LOADS

Service	No. of units	Units operating simultaneously	Current per unit	Operating time	No. of times "On"	Taxying (night) 30 min. Amp.	Taxying (night) 30 min. Amp.-min.	Take-off/Land (night) 10 min. Amp.	Take-off/Land (night) 10 min. Amp.-min.	Cruise (day) 60 min. Amp.	Cruise (day) 60 min. Amp.-min.
Cabin lights	10	10	4	Cont.	Cont	40	1,200	40	400	—	—
Navigation lights	3	3	1	Cont.	Cont.	3	90	3	30	—	—
De-icing actuators	2	2	3	1 sec.	1	6	0·1	6	0·1	6	0·1
Flap actuators	2	2	30	1½ min.	2	60	180	60	180	—	—
Fuel-pump motors	10	10	7	Cont.	Cont.	70	2,100	70	700	70	4,200
Engine-starter motors	4	1	500	½ min.	1	—	—	—	—	—	—
Invertors for instrument supplies	2	1	10	Cont.	Cont.	10	300	10	100	10	600
Radio	1	1	45	Cont.	Cont.	45	1,350	45	450	45	2,700
Cabin conditioning fan	2	2	40	Cont.	Cont.	80	2,400	80	800	80	4,800
Rapid water boiler	1	1	178	8 min.	2	178	2,848	178	1,780	178	2,848
Amp.-minutes							10,468		4,440		15,148
Maximum demand (amperes)						492		492		389	
Average demand (amperes)							348·9		444		252·6

112 volts and are connected in pairs, two port and two starboard, to busbars which form a split busbar system, as described in Chapter 10 (see *Split Busbars*). Each busbar has its individual accumulator and the two busbars have a single interconnector. In the event of a failure of all generators, both accumulators are available to supply power to essential loads, and only in the event of a busbar fault is the capacity of one accumulator lost to the system; 112-volt loads are tactically distributed between the busbars as shown in Fig. 10.39 (*a*). Protection of the generators, accumulators and their feeders is by R.C.C.B's, as described in Chapter 10 (see *Generator to Busbar* and *Accumulator to Busbar*).

The 28-volt supply is obtained from two rotary transformers which each derive power from one of the 112-volt busbars and in turn supply a split-busbar system which is a model of the 112-volt system. These machines provide an output of 3 kW each and, together with their feeders, have differential current protection. They are located, together with their busbars, in close proximity in the fuselage and the busbar interconnector is an H.R.C. fuse link. This fuse is selected to operate only in the event of an earth fault at a 28-volt busbar, or in a convertor output circuit. The unbalance current protection of the 112-volt interconnector is included because the interconnector

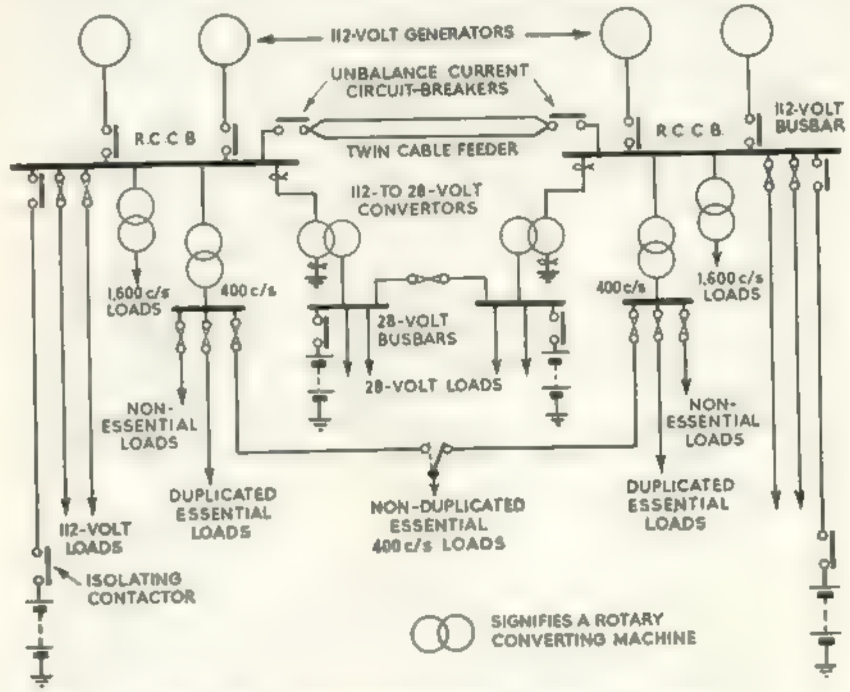


FIG. 11.16. *Principal features of a 112-volt d.c. system.*

is long and therefore has a significant fault potential, and because the unbalance current relays can be set to trip at a relatively low fault current whereas essential fuses must be rated to carry the maximum interconnector current. This is likely to occur when both generators associated with one busbar are inoperative and the convertors are being switched on.

The 400 c/s supply is obtained from two 112-volt d.c. to 400 c/s a.c. motor-generators having outputs of 3 kVA. They are connected to form a non-paralleled system with transfer switching for the non-duplicated essential loads; 1,600 c/s supplies, required only for a few special equipments, are also obtained from motor-generators.

CONSTANT-FREQUENCY ALTERNATING-CURRENT SYSTEMS

THE earliest British constant-frequency a.c. system, so far as the author is aware, was that installed in the "Shetland" flying boats in the years 1948-49. Unfortunately only one of these boats became operational and this was destroyed by fire, caused by mal-operation of the auxiliary generating plant (A.G.P.), shortly after being put into service. The system used two 25 kVA a.c. generators driven by independent sleeve-valve piston engines. Auxiliary generators, consisting of two d.c. generators in a common frame, were also fitted to each A.G.P. to provide excitation for the a.c. generators and to power a small 28-volt d.c. system. Each a.c. generator was capable of providing the maximum power required and parallel operation was not intended, but either a.c. generator could be connected to the system independently.

The system is of special interest because it operated at 250 c/s and employed 8-pole a.c. generators driven at the relatively low speed of 3,750 r.p.m. This was a convenient speed for the auxiliary engine and enabled the a.c. generator rotor to be directly driven and overhung from the engine, which eliminated intermediate gearing and a bearing and end-frame at the driven end. The weight of the a.c. generator was about 60 lb. and the complete A.G.P. about 400 lb.

The first U.S.A. constant-frequency systems are believed to have been installed about 1946 and used the Sundstrand drive, described in Chapter 6. From the outset these systems operated at 400 c/s with a.c. generator speeds of 6,000 r.p.m. and many years of continuous development have followed on the drives and on the electrical system. Most systems employed a.c. generators similar to the one shown in Fig. 6.24 and most of the electrical development was concerned with methods of regulation, parallel operation and protection.

PARALLEL OPERATION OF ALTERNATING-CURRENT GENERATORS

Satisfactory parallel operation requires the regulation of four parameters: (1) frequency; (2) real load sharing; (3) voltage; (4) reactive load sharing.

Frequency can have only one value throughout a paralleled system but this must be regulated within the required limits by equal and simultaneous adjustments to the torques at all the generator drives. Equal adjustments are necessary because the real loads delivered by the a.c. generators are directly related to the torques on their shafts. In a.c. systems, as in d.c. systems, it is preferable to have all the generators operating at equal loads, for the reasons given earlier in this chapter (see *Load Sharing*, page 251).

Real load sharing between a.c. generators is obtained by individual adjustment of shaft torques; this can be appreciated if it is remembered that power input on the shaft is proportional to the product of speed and torque, and that power input and output must be equal, except for the generator losses. Voltage, like frequency, has only one value throughout the system, although if the impedances of the interconnexions between generators should be appreciable, this would not be true. Voltage is regulated by the simultaneous adjustment of generator excitation currents.

The setting of one generator excitation relative to the others determines the manner in which the generators share the reactive load. The optimum arrangement is to have the generators sharing the reactive load equally, just as they should share the real load equally. An alternative way of expressing this is to say that all generators should operate at the same power factor. In addition to equalizing the generator currents, this is desirable because

Table 11.4

SUMMARIZING THE REGULATION OF ALTERNATING-CURRENT SYSTEMS

Quantity to be regulated	*Method of control*
System frequency	Simultaneous and identical adjustments of generator drive torques
System voltage	Simultaneous and identical adjustments of general excitation currents
Sharing of real load between generators	Individual adjustments of generator shaft torques
Sharing of reactive load between generators	Individual adjustments of generator excitation currents

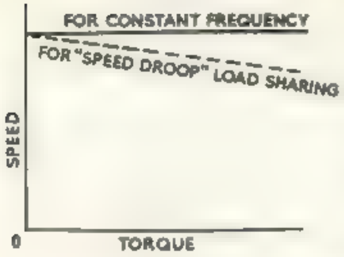


FIG. 11.17. *Alternating-current generator drive speed/torque curves.*

under-excited generators have subnormal synchronizing torques and in an extreme case of under-excitation loss of synchronism can occur.

A summary of the foregoing discussion is given in Table 11.4.

FREQUENCY REGULATION

With the exception of the induction generator, all the a.c. generators mentioned in Chapter 6 generate at a frequency which is proportional to speed. Obtaining the required frequency, 400 c/s, is therefore a matter of ensuring that the a.c. generator drives operate at the appropriate speed. This speed must be maintained under conditions of loading, or load torque, ranging from the very small torque required to overcome no-load losses, to full load or even overload torques. The shaft drive must therefore have a speed/torque characteristic as shown in Fig. 11.17.

The manner of securing this characteristic depends on the type of drive. If the drive is a prime mover such as a piston engine or a gas turbine, the controlled quantity is the fuel, but in the case of air turbines or Sundstrand drives it is the working substance, air and oil respectively.

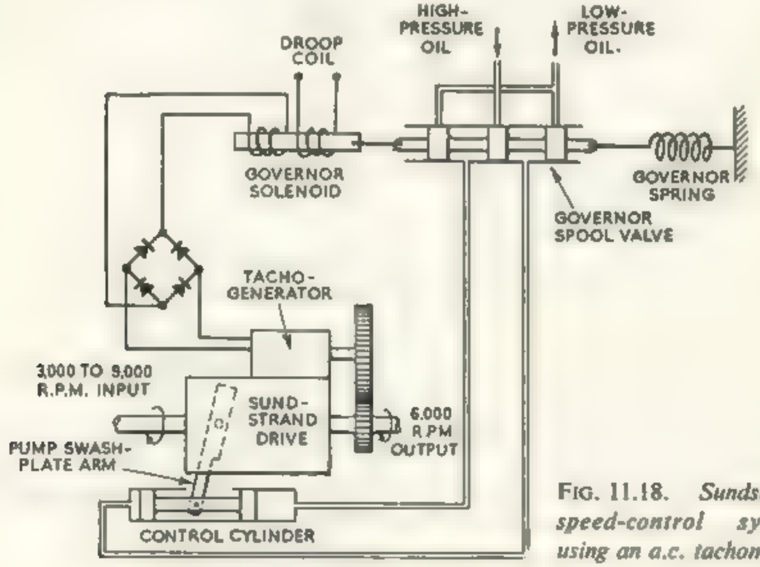


FIG. 11.18. *Sundstrand speed-control system using an a.c. tachometer.*

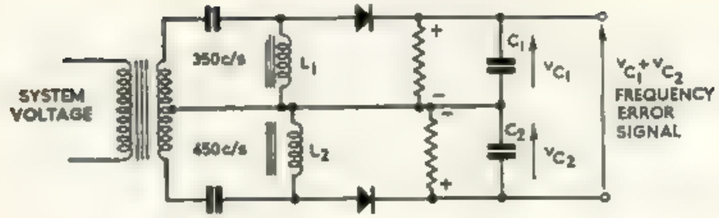


FIG. 11.19. *Frequency-error signal circuit.*

The monitored quantity can be either speed or frequency, but because frequency can be detected only when the generator is functioning, it is usual to monitor speed, at least to secure approximate control. Sundstrand drives, prior to about 1952, used an a.c. tachometer, having a normal speed of 3,000 r.p.m., to provide a signal proportional to speed. This tachometer signal was used to adjust the governor valve setting as shown in Fig. 11.18. Later designs used a centrifugal governor which operated by direct mechanical linkage on the governor valve. The centrifugal governor is preferred because it is simple and is directly connected, but some difficulties have been experienced with its performance under vibration. With both methods the system frequency is primarily dependent on the characteristics and initial setting of the governor valve spring, and the regulation of frequency under varying temperature conditions cannot be expected to be much better than ±2 per cent.

Some of the later systems, employing the centrifugal governor, also

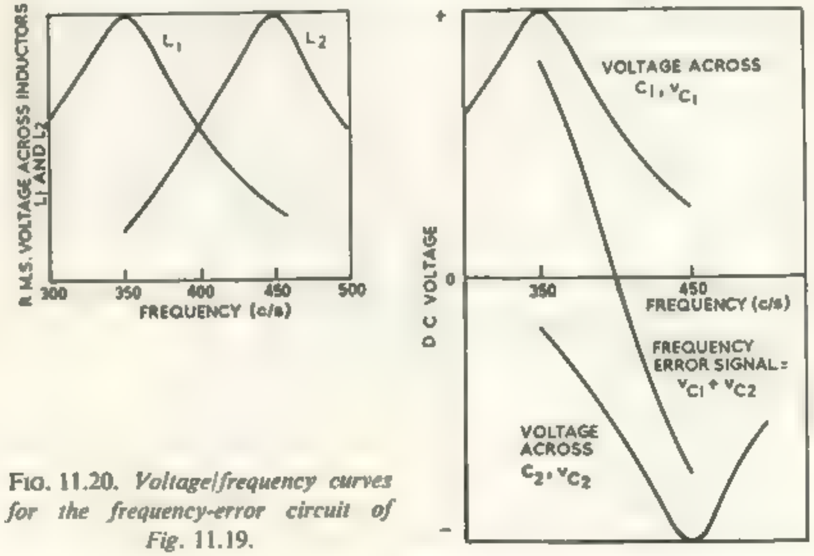


FIG. 11.20. *Voltage/frequency curves for the frequency-error circuit of Fig.* 11.19.

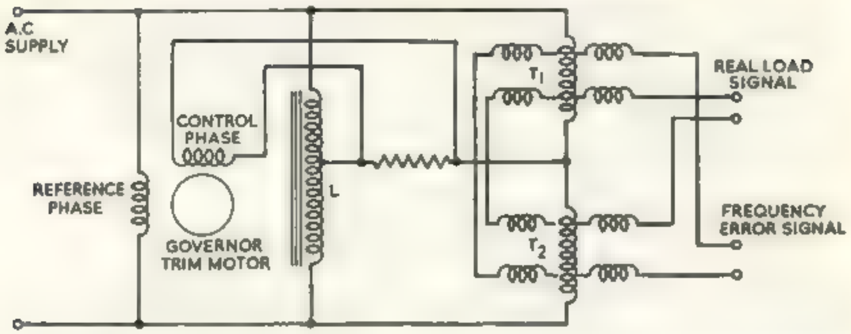


FIG. 11.21. *Sundstrand centrifugal governor trim motor and error signal amplifier.*

incorporate an electrical frequency reference and arrange for the deviation of the system frequency from the reference frequency to cause fine adjustment of the governor valve spring setting. A circuit giving a frequency error signal is shown in Fig. 11.19. This consists of two series inductance-capacitance circuits having resonant frequencies of 350 and 450 c/s. The voltages appearing at several points in the circuit are shown in Fig. 11.20 from which it can be seen how a d.c. error signal is obtained. The magnitude of this error signal increases with frequency deviation from 400 c/s and the polarity depends on the sense of the deviation.

The frequency error signal is used in the circuit shown in Fig. 11.21. T_1 and T_2 are saturable reactors, the reactances of which are changed in opposite senses by the error signal current which is passed through their control windings. Thus any error signal unbalances the a.c. bridge formed by the two parts of the inductor L and the two reactors, and causes voltage to be developed across the resistor. This voltage, which is the amplified frequency error signal, is used to energize the control phase of a two-phase induction motor which is coupled to the centrifugal governor in such a way that rotation of the motor changes the governor spring tension. It should be noted that the error signal derived from the frequency-sensitive circuit of Fig. 11.19 is a d.c. signal and that the circuit of Fig. 11.21, in addition to amplifying the signal, also converts it from d.c. to a.c. High and low frequency, indicated by the polarity of the d.c. signal, are shown by the phase of the a.c. signal with respect to the a.c. supply. Reversal of the phase of the motor control winding current causes reversal of the direction.

A valuable safety feature of the trim motor is that its range of adjustment of the governor spring is limited so that it cannot change the frequency by more than ± 20 c/s. Thus no failure in the frequency-sensitive circuit, amplifier or motor can render the power system completely unserviceable.

With the fine frequency control just described the system frequency,

under steady conditions, can be held to better than $\pm\frac{1}{2}$ per cent or ± 2 c/s over a temperature range of 0 to 50 deg. C. Under changing conditions some widening of these limits is inevitable. For example, when the input speed is changing at 1,000 r.p.m. per second the frequency deviates from its normal value by about 4 c/s; also the sudden removal or application of full electrical load results in a deviation of not more than 20 c/s after about 0·1 second and the disturbance dies away in less than a second.

REAL LOAD SHARING

It is worth repeating that the real loads or watts, delivered by each a.c. generator, will be equal if the generator drive torques are equal. The truth of this statement depends on the assumption that all generators operate at the same efficiency, which is a fair assumption provided they are all operating at the same power factor. If power factors are different, that is, if the reactive load-sharing system is not effective, the generators operating at low power factor will have the greater losses and lower efficiencies. Thus there is some interrelationship between real load sharing and reactive load sharing.

SPEED DROOP METHOD

The earliest and simplest method of real load sharing used drives with falling speed/torque characteristics, as indicated by the broken-line curve in Fig. 11.17. This method is analogous to the voltage-droop method of securing load sharing between d.c. generators, which was discussed earlier (see *Generators with Series Resistors*), and has been similarly called the speed-droop method. To obtain good load sharing it is necessary, in practice, to have speed/torque curves which are nearly linear and a fall of speed from no-load to full load of about 5 per cent. The initial setting of no-load speed is critical and should be set with an accuracy of better than ± 1 per cent. Fig. 11.22 illustrates real load sharing by this method.

Details of a speed-droop circuit, used in conjunction with the Sundstrand drive, are shown in Fig. 11.23. The purpose of the circuit is to develop a voltage proportional to real load which is fed to a droop coil on the

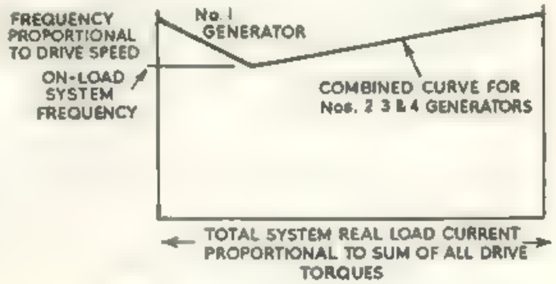


FIG. 11.22. *Illustrating real load sharing by the speed-droop method in a four-generator system.*

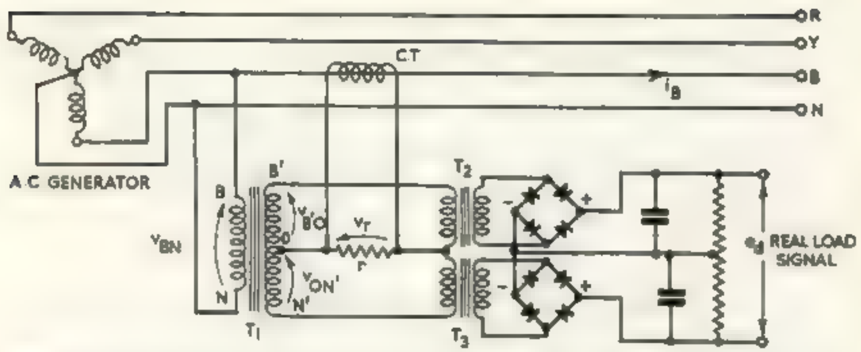


FIG. 11.23. *Speed-droop circuit for real load sharing between a.c. generators.*

Sundstrand governor valve solenoid, as in Fig. 11.18. This voltage, e_d (Fig. 11.23) is developed by combining a phase voltage, v_{BN}, and a voltage, v_r, which is proportional to the corresponding line current, i_B. The phase voltage, v_{BN}, is transformed by the transformer T_1 to a value several times larger than the voltage v_r which is developed across resistor r by the current transformer, *C.T.*, on the blue line. The phase voltage is also split by the centre-tapped secondary winding of transformer T_1 into two equal voltages $v_{B'O}$ and $v_{ON'}$. These voltages are indicated in Fig. 11.23 and the phasor diagram of Fig. 11.24 (*a*).

In the two meshes containing the secondary winding of the transformer T_1 and the primary windings of transformers T_2 and T_3, voltage v_r is added to $v_{B'O}$ and subtracted from $v_{ON'}$ as shown in Fig. 11.24 (*b*). The resulting voltages, v_{T2} and v_{T3}, are impressed on the primary windings of transformers T_2 and T_3 respectively. The secondary voltages of these transformers are subsequently rectified and their difference is taken as the real load signal, e_d. This signal is therefore proportional to the difference between the magnitudes of the voltages v_{T2} and v_{T3}.

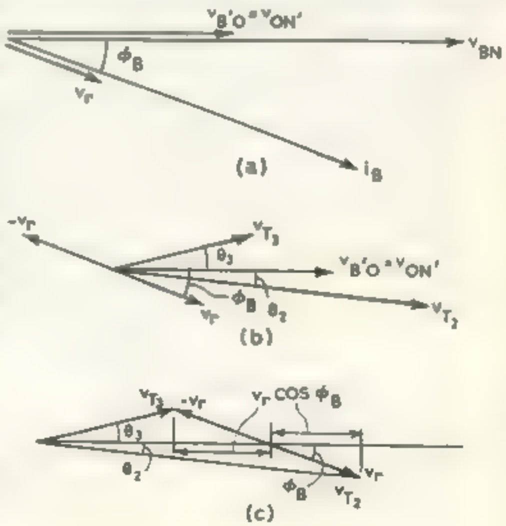


FIG. 11 24. *Illustrating the functioning of the speed-droop circuit in Fig.* 11.23.

Ideally, e_d should be proportional to $i_B \cos \phi_B$, the in-phase component of the blue-line current, and it should be unaffected by $i_B \sin \phi_B$, the reactive component. Thus $v_r \cos \phi_B$ would be an ideal signal because v_r is proportional to i_B. But from Fig. 11.24 (*c*), $v_r \cos \phi_B$ is equal to $\frac{1}{2}(v_{T2} \cos \theta_2 - v_{T3} \cos \theta_3)$ which is half the difference between the horizontal projections of v_{T2} and v_{T3}. This is, generally, not proportional to the difference of the values of v_{T2} and v_{T3}. However, if the angles θ_2 and θ_3 are small, $\cos \theta_2$ and $\cos \theta_3$ are nearly unity and the error is small. This condition can be attained by designing for v_r to be small compared with $v_{B'O}$ and $v_{ON'}$. The practical consequence of this slight discrepancy is that the real load sharing is slightly affected by the reactive load sharing, this effect being independent of the interaction previously mentioned.

EQUALIZING, CONSTANT-FREQUENCY METHOD

In order to achieve load sharing without the undesirable characteristic of frequency falling with increasing load, an equalizing busbar is connected as indicated in Fig. 11.25. The operation of this circuit is similar to that of the regulator equalizing coil circuit for the parallel operation of d.c. generators which is described earlier (see *Regulator Equalizing Coil, Constant-voltage Method*).

Real load unbalance current is defined, as for d.c. generators, as the difference between the real load current of any one generator and the average of all the generator real load currents. In symbols, for a four-generator system

$$i_{up1} = i_1 \cos \phi_1 - \frac{i_1 \cos \phi_1 + i_2 \cos \phi_2 + i_3 \cos \phi_3 + i_4 \cos \phi_4}{4}$$

where i_1, i_2, i_3 and i_4 are the line currents of generators 1, 2, 3 and 4 respectively, the three line currents of each generator being assumed equal, and

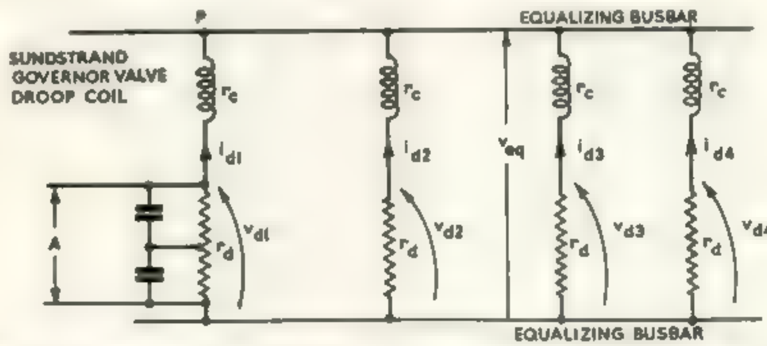


FIG. 11.25. *Equalizing circuit for constant-frequency load sharing: the lines at* A *indicate connexions from the circuit of Fig.* 11.23. (*See also, Fig.* 11.18.)

ϕ_1, ϕ_2, ϕ_3 and ϕ_4 are the corresponding phase angles. The symbol i_{up} is used to identify real load unbalance current and distinguish it from reactive load unbalance current, i_{uq}.

The speed-droop circuit, described in the previous section, was shown to give a real load signal, e_d, which is nearly proportional to the real load current in one of the three lines of a generator. It is a shortcoming of this circuit that it senses the real load current of one line only, but under normal conditions the three line currents are approximately equal and the circuit is satisfactory.

In the circuit of Fig. 11.25, if the impedances of the equalizing busbars are neglected, the potential across all the series circuits consisting of a droop coil and a droop circuit of equivalent resistance, r_d, is equal to v_{eq}. Potentials across individual droop-circuit resistors, v_{d1}, v_{d2} etc., may be different, and in each case $v_d=e_d-i_d r_d$. Considering a four-generator system, the current through the droop coil of the drive governor of No. 1 generator is given by:

$$i_{d1}=\frac{v_{eq}-v_{d1}}{r_c}; \text{ where } r_c \text{ is the resistance of the droop coil.}$$

$$\text{Similarly, } i_{d2}=\frac{v_{eq}-v_{d2}}{r_c}, \text{ etc.} \qquad (10)$$

Summing the current flowing into point P, Fig. 11.25,

$$i_{d1}+i_{d2}+i_{d3}+i_{d4}=0 \qquad (11)$$

Substituting for these currents from equations (10),

$$\frac{v_{eq}-v_{d1}}{r_c}+\frac{v_{eq}-v_{d2}}{r_c}+\frac{v_{eq}-v_{d3}}{r_c}+\frac{v_{eq}-v_{d4}}{r_c}=0$$

Multiplying by r_c and rearranging,

$$v_{eq}=\frac{v_{d1}+v_{d2}+v_{d3}+v_{d4}}{4}.$$

Substituting for v_{eq} in equation (10) for i_{d1}

$$i_{d1}=\frac{1}{r_c}\left\{\frac{v_{d1}+v_{d2}+v_{d3}+v_{d4}}{4}-v_{d1}\right\} \qquad (12)$$

Now, as previously mentioned,

$v_{d1}=e_{d1}-i_{d1}r_d$, $v_{d2}=e_{d2}-i_{d2}r_d$ etc.,

Substituting in equation (12),

$$i_{d1}=\frac{1}{r_c}\left\{\frac{e_{d1}+e_{d2}+e_{d3}+e_{d4}}{4}-r_d\frac{(i_{d1}+i_{d2}+i_{d3}+i_{d4})}{4}-e_{d1}+i_{d1}r_d\right\}$$

$$=\frac{1}{r_c}\left\{\frac{e_{d1}+e_{d2}+e_{d3}+e_{d4}}{4}-e_{d1}+i_{d1}r_d\right\} \qquad (13)$$

since $i_{d1}+i_{d2}+i_{d3}+i_{d4}=0$, equation (11).

Now, $e_{d1}=ki_1\cos\phi_1$ approximately, as shown under *Speed Droop Method*, where k is a constant depending on the design of the speed droop circuit

and is equal to the output e.m.f. of the droop circuit in volts per amp. of in-phase line current.

Similarly, $e_{d2}=ki_2\cos\phi_2$ etc.,

Substituting in equation (13)

$$i_{d1}=\frac{1}{r_c}\left\{\frac{ki_1\cos\phi_1+ki_2\cos\phi_2+ki_3\cos\phi_3+ki_4\cos\phi_4}{4}-ki_1\cos\phi_1+i_{d1}r_d\right\}$$

$$=\frac{1}{r_c}\left\{k(-i_{up1})-i_{d1}r_d\right\} \text{ since, by definition,}$$

$$i_{up1}=i_1\cos\phi_1-\frac{i_1\cos\phi_1+i_2\cos\phi_2+i_3\cos\phi_3+i_4\cos\phi_4}{4}$$

$$\text{Rearranging, } i_{up1}=-i_{d1}\left\{\frac{r_c+r_d}{k}\right\} \qquad (14)$$

Thus the droop coil current of No. 1 generator is proportional to its real load unbalance current and, if the droop coil is correctly sensed, tends to correct the unbalance by adjusting the drive torque.

Now i_d flowing through a governor droop coil causes a change of torque δT. Let $\delta T/i_d=K$, a constant dependent on the design of the droop coil and governor. When all generators are delivering equal real load currents all shaft torques should be identical at some value T. These torques may be considered to be made up of two increments, T_1, the torque with zero droop coil current, and δT_1, the torque correction caused by the droop coil current, in the case of No. 1 generator drive.

Thus, $T_1+\delta T_1=T$. Substituting for δT_1,

$$T_1+Ki_{d1}=T. \text{ Hence, } i_{d1}=\frac{T-T_1}{K}$$

Substituting for i_{d1} in equation (14),

$$i_{up1}=\frac{T_1-T}{K}\times\frac{r_c+r_d}{k} \qquad (15)$$

T_1-T may be regarded as approximately the torque error, the amount by which the torque determined by the speed governor requires correction to give perfect load sharing. It is not exactly the error, because the load-sharing system is not perfect; neither does it take account of the fact that differences between generators will require that the torques are slightly different if perfect load sharing is to be achieved. Equation (15) shows that for minimum unbalance current with a given torque error the constants K and k should be large and the resistances of the droop coil and speed-droop circuit output should be small.

The types of Sundstrand drive employing a centrifugal governor cannot readily use a droop coil, either to obtain a falling speed/torque characteristic or to obtain load sharing at constant speed. The real load signal can, however, be impressed on the centrifugal governor by adjustment to its spring setting

and this is achieved by using the signal to operate the motor used for fine frequency control. Amplification and conversion to an a.c. signal is achieved by feeding the d.c. signal to windings on the transductors, T_1 and T_2, of the trim motor amplifier, which is shown in Fig. 11.21. As the control of the trim motor is restricted to about ± 20 c/s, no failure of the load-sharing circuit can render the power system inoperative, although parallel operation would almost certainly be impossible.

With this type of governor and load-sharing circuit, unbalance current under steady conditions is less than 7·5 per cent of the ideal current at full load. Under changing conditions of load or input speed the unbalance may increase to 25 per cent. These values of unbalance current could be reduced, as previously suggested, by using high values for the constants K and k, but in practice, as in d.c. systems, high values for these constants lead to instability. One case is reported of a system of two paralleled generators in which high sensitivity has caused instability described as a shift of the entire load from one drive to the other in an oscillatory manner at a frequency of about one cycle per second (Ref. 17).

VOLTAGE REGULATION

The voltage regulation of a.c. generators has been discussed in Chapter 6 (see *Excitation and Voltage Regulation*). In three-phase systems the voltage signal is usually derived from a three-phase bridge rectifier, the output of which is closely proportional to the mean value of the three line voltages. Stabilizing transformers, as described in Chapter 5 (see *Voltage Regulator*) are often connected between the rectifier output and the regulator voltage sensing coil.

REACTIVE LOAD-SHARING, VOLTAGE-DROOP METHOD

Alternating-current generators share a reactive load equally if the generator voltages are made to fall as the reactive load is increased, provided the initial voltage settings and the voltage reactive load characteristics are identical. As with other droop methods of load sharing, these conditions are difficult to achieve and maintain to the degree of accuracy necessary for good sharing, and even if they could be achieved the system would still have the undesirable characteristic of voltage falling as the reactive load is increased. Because of these things, and probably because the regulator equalizing coil method of load sharing in d.c. systems had become well established, a.c. systems used equalizing methods of reactive load sharing almost from the beginning.

A droop circuit adopted for reactive load sharing is shown in Fig. 11.26. This, alone, would enable a system to operate with reactive load sharing by the droop method, but it will be shown later that these circuits

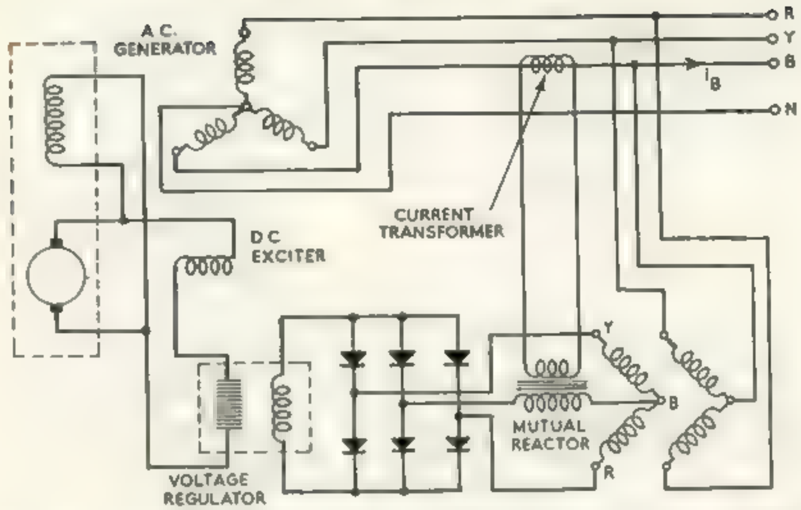


FIG. 11.26. *Voltage-droop circuit for reactive load sharing between generators.*

can be interconnected by reactive load equalizing busbars to give reactive load sharing and constant system voltage. The circuit is essentially a voltage-regulation circuit with two additional components, a current transformer and a mutual reactor which is sometimes called an equalizing transformer. The circuit employs a vee-vee transformer to transform the system voltage to a level suitable, after rectification, for the voltage sensing coil of the regulator. At such low power levels this type of transformer is simpler and slightly lighter than a normal three-phase transformer.

If the mutual reactor secondary winding is short-circuited it can be seen that the voltage regulator sensing coil would be supplied with a voltage proportional to the mean value of the three line voltages. If the mutual reactor is connected as shown, any voltage appearing at its secondary terminals is added to one of the three transformed line voltages and the rectifier output will almost certainly be affected. This would affect, in turn, the voltage regulator sensing coil current, the exciter field current and the a.c. generator excitation. Before proceeding it will be necessary to examine the mutual reactor and determine the nature of its output.

A mutual reactor is a transformer having a large air-gap in the flux circuit. Because of this the magnetizing current is relatively large, and in this application it is a large part of the total primary current. Fig. 11.27 shows a phasor diagram for such a transformer. The diagram has been drawn showing an unusually large magnetizing current, i_m, and a slightly inductive secondary load circuit, indicated by the small angle ϕ_2. With these conditions it is shown that the secondary voltage, v_2, lags the primary current i_1, by approximately

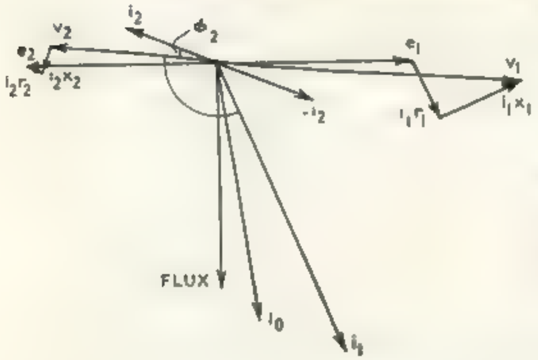


FIG. 11.27. *Phasor diagram for a mutual reactor. The diagram is drawn for a 1 : 1 ratio.*

90 deg. A practical value is about 100 deg. Having established this relationship it is now possible to determine how the mutual reactor output affects the rectifier output.

Fig. 11.28 (*a*) shows a diagram of phase and line voltages for the system. Consider first the case when the line current, i_B, is in phase with the phase voltage v_{BN}, and the consequent voltage at the secondary terminals of the mutual reactor is v_{mr}. These quantities are shown in Fig. 11.28 (*b*). Then consider the case when the current i_B is lagging 90 deg. behind v_{BN}, as shown in (*c*). Now consider the three voltages which are impressed on the rectifier in both these cases. The mutual reactor secondary voltage, v_{mr}, is added to v_{YB}, and subtracted from v_{BR} as shown in (*d*) and (*e*).

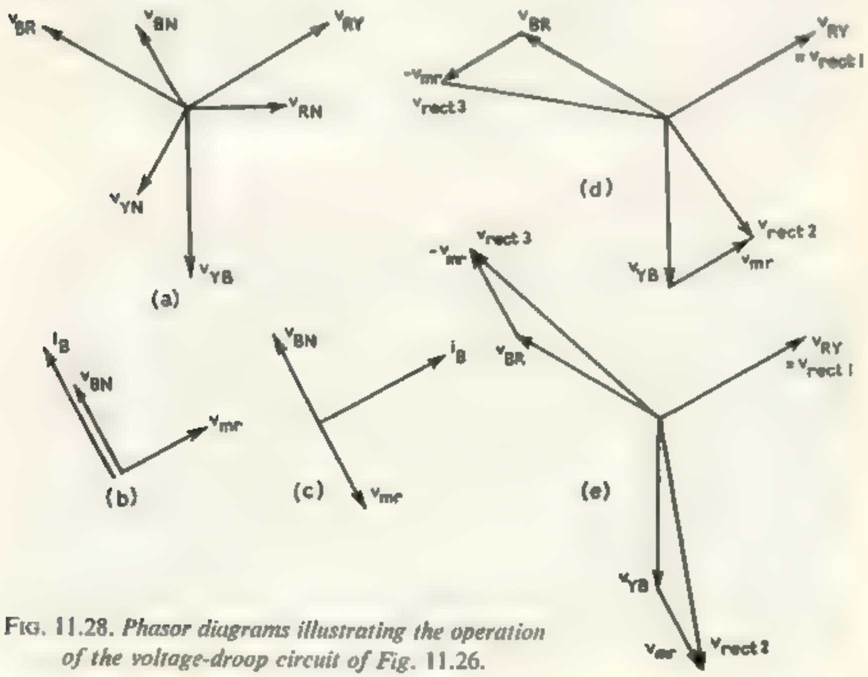


FIG. 11.28. *Phasor diagrams illustrating the operation of the voltage-droop circuit of Fig.* 11.26.

It can be seen that when the current i_B is in phase with v_{BN} the rectifier voltages are different but the mean value is practically unchanged. When the current i_B is lagging v_{BN} by 90 deg., two of the three rectifier voltages are again affected by v_{mr} but in this case both voltages are increased. The mean rectifier output is therefore increased and the voltage regulator reduces the a.c. generator excitation and thereby reduces its reactive load current. Thus the circuit of Fig. 11.26 is sensitive to reactive load current but not to real load current.

EQUALIZING, CONSTANT VOLTAGE METHOD

This is similar to the equalizing methods of real load sharing of d.c. and a.c. systems. Fig. 11.29 shows how the components of the droop circuit (Fig. 11.26) can be interconnected to give an equalizing circuit.

Unbalance reactive load current, i_{uq}, is defined in the same manner as unbalance real load current. In a four-generator system the unbalance reactive load current of No. 1 generator is defined as

$$i_{uq1}=i_1 \sin \phi_1-\frac{i_1 \sin \phi_1+i_2 \sin \phi_2+i_3 \sin \phi_3+i_4 \sin \phi_4}{4} \qquad (16)$$

It follows from this definition, as may be confirmed for unbalance real load currents of a d.c. system from Table 11.1, that the sum of all the unbalance reactive load currents is zero. Adding voltage drops around the loop containing the mutual reactor primary windings and equating to zero:

$$i_{m1}z_m+i_{m2}z_m+i_{m3}z_m+i_{m4}z_m=0$$

where i_{m1}, i_{m2} etc., are the primary currents of the mutual reactors associated with generators 1, 2 etc., and z_m is the effective impedance of a mutual reactor primary winding.

Dividing by z_m, $\quad i_{m1}+i_{m2}+i_{m3}+i_{m4}=0 \qquad (17)$

In order to relate the mutual reactor primary currents to the generator

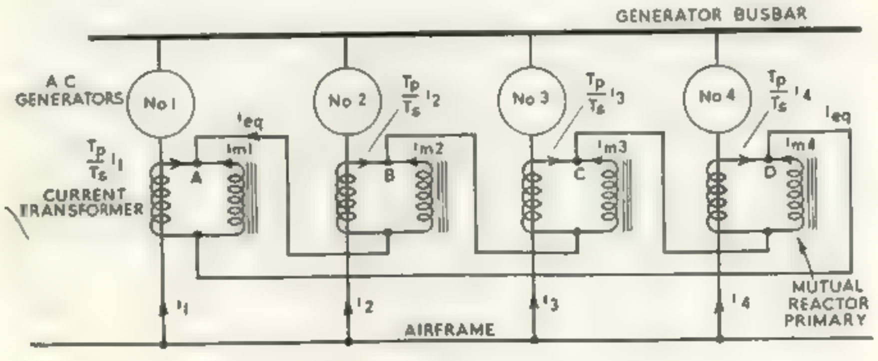


FIG. 11.29. *Reactive load equalizing circuit for a four-generator system.*

unbalance currents, consider points A, B, C and D in Fig. 11.29. Adding the currents flowing in to these points:

at point A, $$\frac{T_p}{T_s}i_1+i_{eq}+i_{m1}=0 \quad (18)$$

Similarly, at point B,

$$\frac{T_p}{T_s}i_2+i_{eq}+i_{m2}=0 \text{ etc.} \quad (18a)$$

where T is a number of turns, and suffixes p and s refer to the primary and secondary windings, respectively, of the current transformer, and i_{eq} is the current indicated in Fig. 11.29. Adding equations (18) and (18a) for a four-generator system gives

$$\frac{T_p}{T_s}(i_1+i_2+i_3+i_4)+(i_{m1}+i_{m2}+i_{m3}+i_{m4})+4i_{eq}=0$$

But, from equation (17), $i_{m1}+i_{m2}+i_{m3}+i_{m4}=0$, hence

$$i_{eq}=-\frac{T_p}{T_s}\frac{(i_1+i_2+i_3+i_4)}{4} \quad (19)$$

Substituting for i_{eq} in equation (18) for currents at the point A,

$$\frac{T_p}{T_s}i_1+i_{m1}-\frac{T_p}{T_s}\frac{(i_1+i_2+i_3+i_4)}{4}=0$$

Hence, $$i_{m1}=-\frac{T_p}{T_s}\left\{i_1-\frac{i_1+i_2+i_3+i_4}{4}\right\}=-\frac{T_p}{T_s}i_{u1} \quad (20)$$

by the definition of i_{u1} (see *Generators with Series Resistors*). Corresponding equations can be developed for the primary currents of the other mutual reactors. Thus, when connected as shown in Fig. 11.29, mutual reactor primary currents are proportional to their respective generator unbalance currents, real and reactive together, but not to the total generator currents. These mutual reactor currents give rise to secondary voltages which, as explained with the aid of Fig. 11.27, are approximately in quadrature with the currents. It has also been explained from Fig. 11.28 that the output of the voltage regulator rectifier is affected only by the component of mutual reactor secondary voltage which is caused by the reactive component of generator unbalance current. Thus the effective component of No. 1 mutual reactor secondary voltage, v_{m1}, may be expressed in terms of mutual reactor primary current as follows: $v_{m1}=ki_{m1}\sin\phi_1$, where k is a constant taking account of the mutual reactor turns ratio and the effect of mutual reactor voltage on the rectifier output, and ϕ_1 is the phase angle between generator current and voltage. Substituting for i_{m1} from equation (20),

$$v_{m1}=-k\frac{T_p}{T_s}i_{u1}\sin\phi_1 \quad (21)$$

Now, the voltage sensed by the voltage regulator is proportional to the system voltage, v, and the effective component of mutual reactor secondary

voltage, v_m, and the regulator functions so that $v+v_m=v_{ref}$, where v_{ref} is the voltage at which the regulator is set to control.

Substituting for v_{m1} from equation (21),

$$v-v_{ref1}=k\frac{T_p}{T_s}i_{u1}\sin\phi_1$$

or, $$i_{u1}\sin\phi_1=i_{uq1}=\frac{T_s}{kT_p}(v-v_{ref1}) \quad (22)$$

Equation (22) shows how the unbalance reactive current, i_{uq}, is related to an error in the regulator setting v_{ref}. As in the equalizing circuits previously considered, there are some constants which can be chosen to minimize the unbalance current for a given voltage error but, as before, values which give the best load sharing also give the least stable circuits. Practical values for the constants in equation (22) are: $T_s=50$, $T_p=1$, and $k=10$ volts per amp. With these values a 1 per cent negative error in the setting of the voltage regulator of a 200-volt system gives rise to an unbalance reactive current, i_{uq},

$$=\frac{50}{10\times 1}(200-198)=10 \text{ amp.}$$

It should be noted that, with one generator voltage set a little low, the other generators, if they have the same settings, must all be set a little high. Since the unbalance currents add to zero, equation (16), the unbalance currents of the other generators in the example are $-10/3=-3\cdot3$ amp. Rearranging equation (22) and applying it to No. 2 generator

$$v_{ref2}=v-\frac{kT_p}{T_s}i_{uq2}$$

$$=200-\frac{10\times 1}{50}\times(-3\cdot3)=200+0\cdot66=200\cdot66 \text{ volts.}$$

The notes on the dangers of *Equalizing Circuits* (page 259) also apply to this reactive load-sharing circuit, except that this circuit is isolated electrically from the system and from the airframe. At least one fault is therefore possible without affecting its operation. This is also true of the real load-sharing circuit discussed under *Equalizing, Constant-voltage Method*. Continued operation in the event of an open-circuit fault can be assured by duplicating the loop carrying the equalizing current, i_{eq}.

Earthing. It is usual to earth the neutral or star points throughout a constant-frequency a.c. system. The possibility of using the airframe to replace one of the three line conductors is attractive because it would save weight but would inevitably unbalance the system owing to the different resistance and inductance of the earthed line. At present it is not known whether such a scheme is practicable or not. Small a.c. supplies, derived from convertors, are usually connected in this way, and appear to operate satisfactorily.

FOUR-GENERATOR SYSTEM

Layout. Fig. 11.30 shows a layout for a four-generator system which is typical of present practice and is notable for allowing a high degree of flexibility in operation. It is an example of an extreme case of a split busbar system as shown in Fig. 10.40 (*b*). Normal operation is with all generators connected in parallel but in the event of a fault it is intended that the most expedient alternative mode of operation shall be selected, either automatically or manually.

Each generator is associated with a group of loads to which it can supply power independently with the minimum of intervening circuitry or control

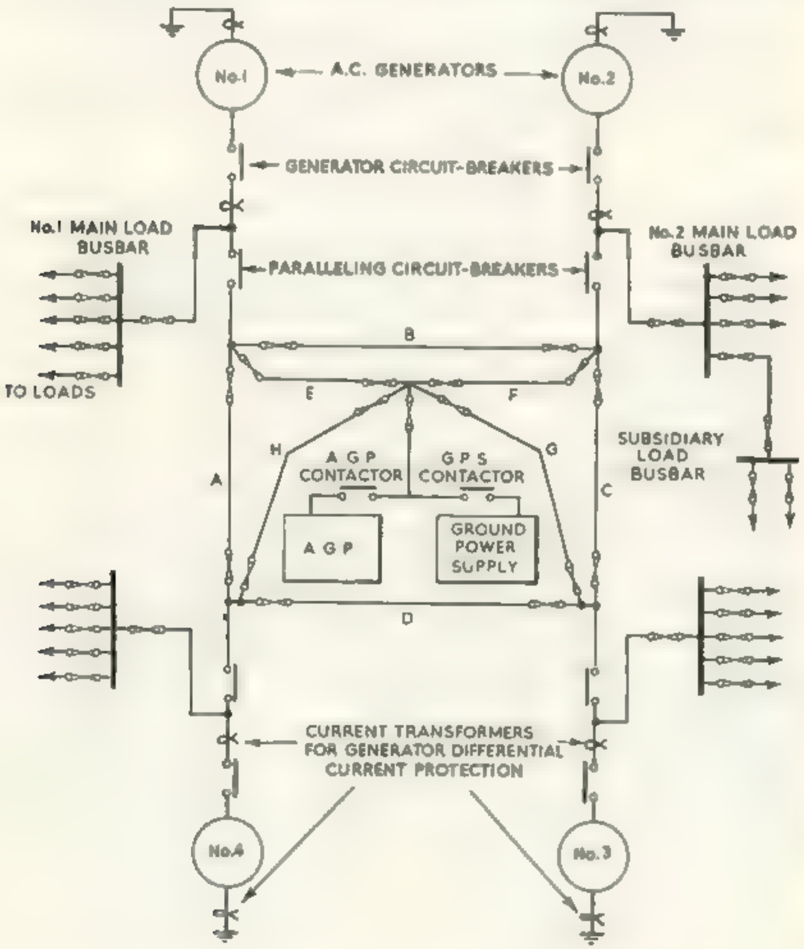


FIG. 11.30. *A layout for a four-generator constant-frequency power system.*

equipment. To be compatible with this principle, the essential loads are also divided, as far as possible, into four groups, one of which is connected to each load busbar. The paralleling circuits, normally in use, are in the form of a mesh, consisting of feeders *A*, *B*, *C*, *D* and a star of feeders *E*, *F*, *G*, *H*. With this arrangement the isolation of any one load busbar cannot occur unintentionally unless three failures occur; failures of feeders *C*, *F* and *B* in the case of No. 2 load busbar. In military aircraft these feeders follow different paths to minimize the risk of three such failures occurring simultaneously.

Failure of an individual generator, or faults in its feeder, cause the operation of the associated generator circuit-breaker, but the supply to the loads associated with that generator is uninterrupted if the system is paralleled. Failure of two or more generators may leave the remaining generators overloaded. This can be remedied by isolating the operational generators with their respective loads, which is done by opening their paralleling circuit-breakers, and connecting the A.G.P. to the remaining loads through the paralleling feeders. This mode of operation presupposes that the A.G.P. cannot be operated in parallel with the generators. This is the case in some present systems but is not fundamentally impracticable.

Many other modes of operation are possible in flight by selecting various combinations of generator and paralleling circuit-breaker settings and by using the A.G.P. On the ground, either the ground supply or the A.G.P. can supply power to any or all load busbars.

PROTECTION

Each of the main feeders shown in Fig. 11.30, since it is a three-phase system, consists of three lines. Protection by triplicating and fusing each line, as described in Chapter 10 (see *Main Feeders*) would be possible but would be complicated and probably unnecessary. From the layout of the system three independent routes exist between any two supply and load points. For example, between the paralleling circuit-breakers of Nos. 1 and 2 generators the three routes are via feeders *B*, *ADC*, and *EF*. Under normal conditions, each feeder has a power source at both ends and if it is fused at both ends it will be isolated in the event of a short-circuit fault. Thus a single earth fault will only reduce the number of paths between these two points from three to two, and three independent faults, in the same phase, would be necessary before they were separated. The feeders from the main load busbars to subsidiary load busbars, and to important individual loads, may be triplicated and fused to ensure continuity of supply in the event of one feeder fault.

Faults on the small sections of feeder between each main load busbar and the paralleling feeder fuses, including the paralleling circuit-breakers, render these sections inoperative. These sections could be triplicated and

fused or they could be practically eliminated by adjacent positioning of each paralleling circuit-breaker and the corresponding feeder and busbar fuses. As shown, they have a fault potential similar to that of busbars. One fault must cause all three adjacent feeder fuses to operate, the associated generator must be de-energized and the load busbar is isolated. These circumstances can be justified only if the sections are of small physical dimensions and have adequate mechanical protection.

Line-to-line and line-to-earth faults in the generators or on the generator feeders, up to and including the generator circuit-breakers, are detected by a differential current sensing circuit which, through a relay, de-energizes the generator and opens the generator circuit-breaker. The paralleling circuit-breaker is not opened and the supply to the associated generator loads is therefore uninterrupted.

Operation. A 28-volt d.c. supply is necessary to operate the system in order to trip all the generator circuit-breakers and close all the paralleling circuit-breakers. With the circuit breakers thus set, ground power may be connected to the system. Alternatively, the A.G.P. may be started, but interlocks prevent both sources being connected to the system simultaneously. Alternating-current power is then available at all load busbars where it is required for such things as fuel-pump operation prior to engine starting.

On starting an engine, and switching on the corresponding generator, the paralleling circuit-breaker is opened and the generator circuit-breaker closed. This may be an automatic sequence, minimizing the period for which the load busbar is disconnected from a supply. After all engines are started and generators switched on, each load busbar is connected to its corresponding generator, and the ground supply or A.G.P. is then unloaded and can be switched off.

Synchronizing and paralleling, which should be recognized as distinct operations, can then be carried out. Paralleling is simply the connexion of two power sources in parallel, in this case the connexion of any generator and one or more other generators to the paralleling feeders. It is effected by closing the appropriate paralleling circuit-breaker. Synchronism is achieved, strictly, when the two sources have identical frequencies and are in phase but, in this application, synchronism is generally understood to mean that the two sources are adjusted to similar frequencies and are momentarily in phase. Synchronism and phasing can be determined by the simple expedient of connecting a lamp across one line of the paralleling circuit-breaker of the generator to be synchronized, as shown in Fig. 11.31. Normally the two a.c. sources will not be exactly in synchronism because the frequency regulators are unlikely to control at identical frequencies. The phase relationship between corresponding phases of the two sources is therefore, generally, changing, passing through complete cycles at a frequency which is the

difference of the two source frequencies, and the lamp is alternately bright and dark.

The first generator to be connected to the system paralleling feeders can be connected without any synchronizing procedure because the system is not energized. The second and subsequent generators should be synchronized and the circuit-breaker closed at an instant when the synchronizing lamp is dark. With properly adjusted regulators, synchronism is likely to be fairly close, probably to within half a cycle a second, and under these conditions frequency adjustment is not likely to be necessary.

On closing down the system the loss of drive to a generator causes the underspeed detection circuit to open the generator circuit-breaker but, because the paralleling circuit-breaker remains closed, the supply to load busbars is maintained until the last generator is disconnected.

SPECIFICATION OF AN ALTERNATING-CURRENT POWER SUPPLY

Much of the discussion under *Specification of a Direct-current Power Supply* is also applicable to an a.c. supply. Additional significant quantities are: (1) the system frequency; (2) unbalance between phase voltages, both in phase and magnitude; (3) waveform; (4) phase sequence. Before discussing these, it should be noted that when specifying the voltage of a three-phase a.c. system it is necessary to specify either the line or the phase voltage because, owing to imperfections in the supply such as slightly different phase displacements between phase voltages, the ideal ratio between phase and line voltages of $1 : \sqrt{3}$ is not exactly applicable.

System frequency limits are defined for steady conditions in the same manner as voltage limits. The effects of disturbances, however, are much less severe on frequency than on voltage, owing to the relatively high mechanical inertias of the generators and their drives, and it is generally sufficient to specify a minimum acceptable frequency for the time immediately following a fault. Typical steady-state limits are ± 20 c/s, and a lower limit applicable under fault conditions is -40 c/s.

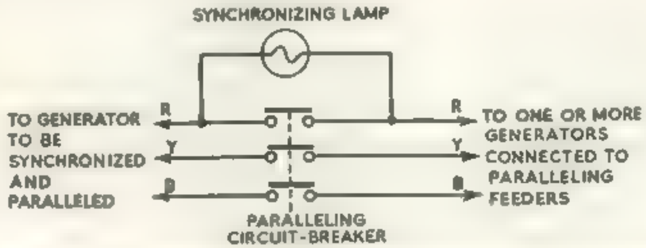


Fig. 11.31. *Arrangement of a lamp and circuit-breaker for synchronizing and paralleling.*

The meaning of unbalance between phase voltages is a matter of definition. One definition is: Maximum deviation from average/Average. For example, if the three-phase voltages are 112, 116 and 117 volts, the average phase voltage is 1/3 of (112+116+117) which is 115 volts. The maximum deviation is 115−112 which is 3 volts. By the foregoing definition, unbalance between phase voltages is therefore 3/115, or 2·6 per cent. A reasonable limit for this quantity is about 4 per cent. Phase displacement between phase voltages should ideally be 120 deg. but a tolerance of ± 4 deg. is generally acceptable.

Waveform is a difficult quantity to specify in order to preclude all forms which may be troublesome, without being impracticable. A compromise is to specify a limit for the total harmonic content in terms of the r.m.s. value of the fundamental frequency voltage, and also to set a limit on the ratio of peak to r.m.s. voltage of the distorted waveform; 5 per cent harmonic content and ± 10 per cent departure from the ideal ratio of peak to r.m.s. voltage, $\sqrt{2}$, are practicable values.

Phase sequence is inherent in a three-phase system. Its specification is therefore superfluous. Neither does it require tolerances. It is necessary, however, in order to avoid mistakes in manufacture and servicing, to specify terminal markings for all components of the system and the sequence of the phase voltages at these terminals.

RECTIFIED ALTERNATING-CURRENT SYSTEMS

Introduction. This kind of system has been chosen in Britain for many post-war civil aircraft and for at least one large military aircraft. In the U.S.A., however, the system has not been favoured to the same degree, although it has been extensively considered and used. Alternating-current generators and rectifier units were in use for the radio-transmitter h.t. supplies in very early aircraft and, at that time, U.S.A. designers preferred them to high-voltage d.c. generators, but the extension of the principle to power systems has been pursued more by British designers. It is likely that the earliest British application was in the Vickers Supermarine "Seagull", shortly after the second world war. This installation used a single-engine-driven a.c. generator having outputs of 7·5 kVA and 1·2 kVA at 400 and 1,600 c/s respectively. Approximately 2 kVA of the 400 c/s output was fed to a transformer-rectifier unit, which had a 28-volt d.c. output of 50 amp. and a low-voltage a.c. output of about 300 watts.

The availability of selenium rectifiers, which are discussed in Chapter 8, helped to make the system competitive with d.c. systems from the weight

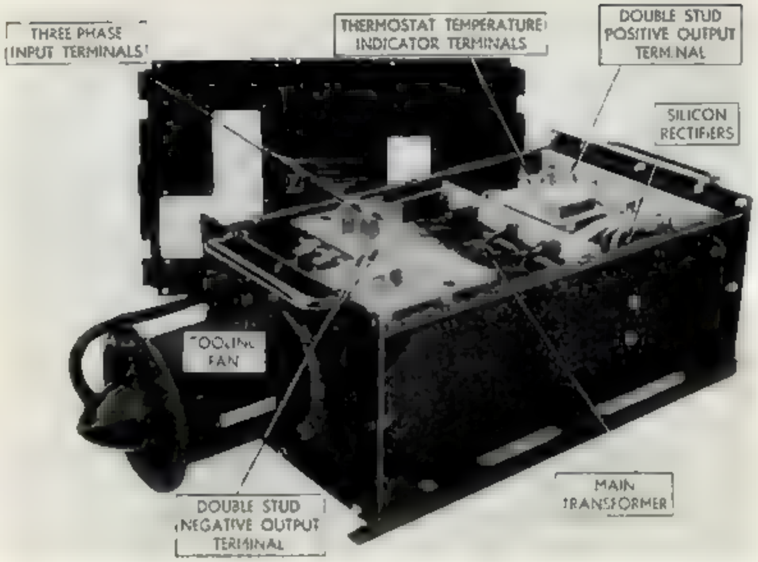


FIG. 11.32. *Transformer-rectifier unit having an output of 500 amperes at 28 volts. The main transformer is shown in Fig.* 8.12, *and similar units in Fig.* 10.39.

aspect, but the volume of these rectifiers was always a minor embarrassment. This has now been overcome by the introduction of silicon rectifiers, which are also discussed in Chapter 8.

Rectified a.c. systems were preferred to d.c. systems because the a.c. generator is much less affected by poor brush performance at high altitude, and because the advent of electrical de-icing had created a need for large quantities of power. The nature of this power and, in particular, its frequency if it is a.c., are not critical. The demand could therefore be met with engine-driven a.c. generators, the low specific weight of which, 2 to 3 lb. per kW, permitted a substantial weight saving.

The rectified outputs of each a.c. generator in a system are normally paralleled, as in a d.c. system, but the a.c. outputs, since they are not synchronized, must be independent. Provision for powering all the essential a.c. loads in the event of a generator failure, is therefore required. This generally takes the form of transfer switching, allowing each load busbar to be connected to one or more alternative generators.

TRANSFORMER-RECTIFIER UNITS (T-R UNITS)

This name is often used to describe the units containing most of the components of a rectified a.c. generating channel, other than the generator,

FIG. 11.33. *Transformer-rectifier unit having an output of 500 amp. at 28 volts d.c. The rectifier assembly is shown in Fig.* 8.18.

many of which are transformers and rectifiers. Typical T-R units are shown in Figs. 11.32 and 11.33. In most cases they have been designed with internal cooling air channels and, to ensure cooling while the aircraft is stationary, cooling fans, as shown in Fig. 11.32, have often been built-in. Many early T-R units included carbon-pile voltage regulators which, together with the other components, were intended to be serviced only when the complete unit had been removed from the aircraft. There is some evidence that the reliability of such components as regulators and relays was not adequate to make this arrangement satisfactory, and some later designs give accessibility of these components while the T-R unit is in the aircraft. Modern designs, such as those shown, exclude most of these components. The introduction of magnetic amplifier-type regulators favours the comprehensive unit.

Fig. 11.34 is a block diagram of a rectified a.c. generating channel. Most of the items shown in the diagram have been included in T.R units, particularly those of earlier design. The following Sections discuss these items in detail.

MAIN TRANSFORMER

Whether or not this item is needed depends on the relative voltages of the a.c. generator and the a.c. and d.c. outputs. If these are standard aircraft voltages, 200 volts a.c., 112 and 28 volts d.c., a transformer or equivalent device is necessary, since only one output can be obtained directly from a simple a.c. generator. The lightest arrangement is, generally, to choose the a.c. generator voltage to suit the largest output, in terms of power, and to transform the others.

The primary windings of main transformers have, in some systems, been tapped and used as auto-transformers, as indicated in Figs. 11.35 (*a*) and (*b*). In the case of the Airspeed "Ambassador", the primary tapping was used

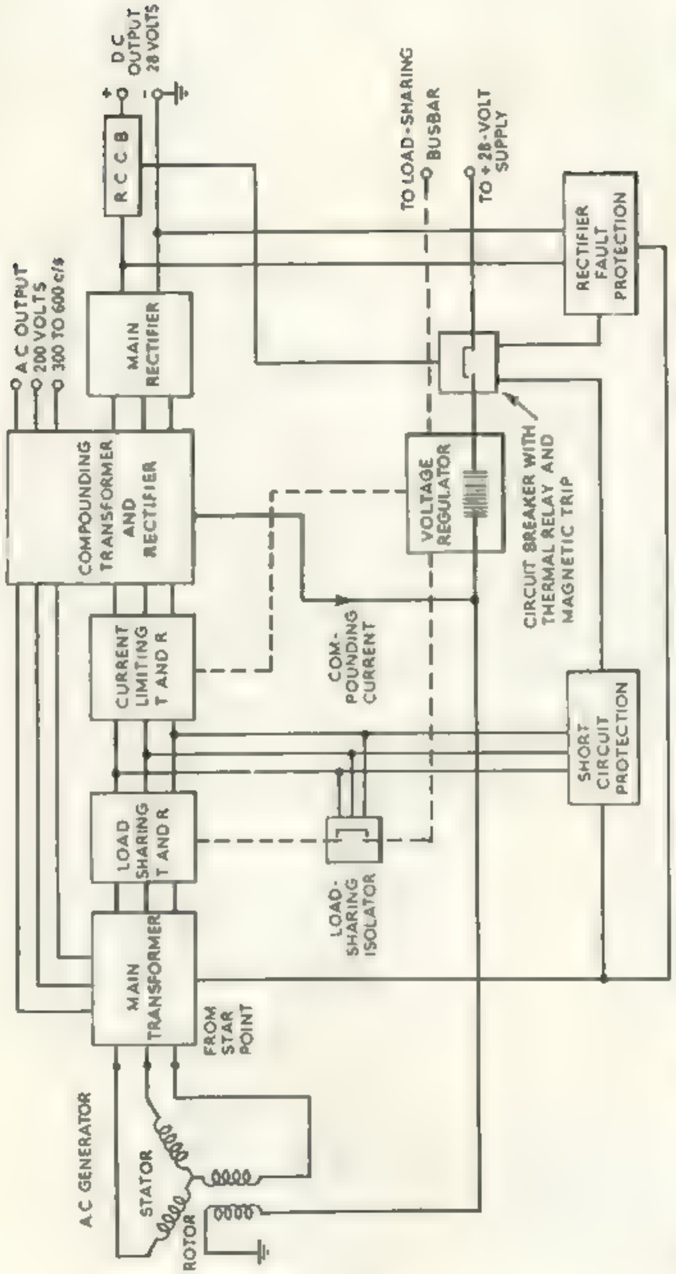


FIG. 11.34. *Generating channel of a rectified a.c. system. The abbreviations* T *and* R *refer to transformer and rectifier. R.C.C.B. indicates reverse-current circuit-breaker.*

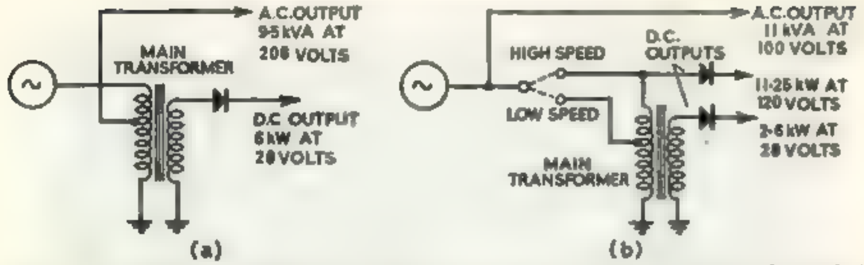
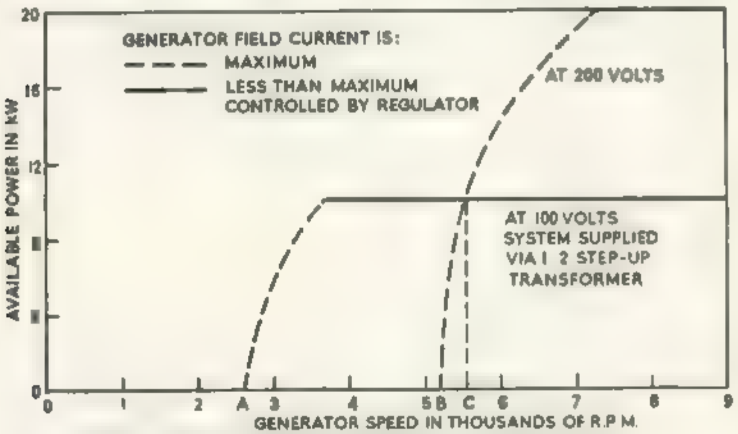


FIG. 11.35. *Equivalent single-phase diagrams of transformer connexions of rectified a.c. systems;* (a) *Airspeed "Ambassador" system;* (b) *Handley Page "Hermes" system.*

solely to obtain a.c. power at 208 volts (then a standard voltage) but the tapping on the transformer of the Handley Page "Hermes" system served the additional purpose of extending the speed range over which the a.c. generator could function usefully. This principle is used in later systems and will be considered in detail.

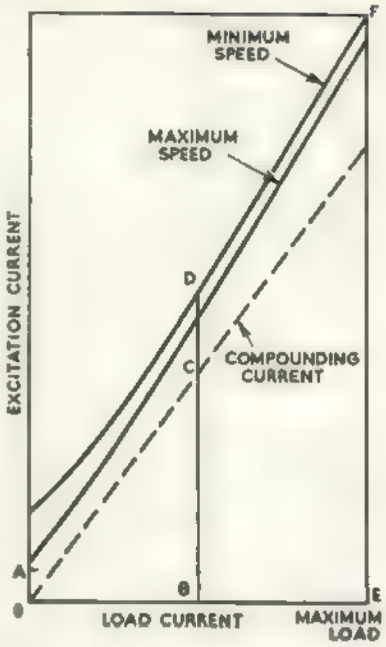
For any generator on open-circuit and with constant excitation, voltage is proportional to speed. Thus there is a minimum speed at which the system voltage can be generated, even with full excitation. This is indicated by point *B* in Fig. 11.36, on a curve relating available power at 200 volts to generator speed. If, however, an a.c. generator is followed by a step-up transformer, power may be obtained at system voltage at a lower generator speed. This is



SPEEDS	EFFECT OF TRANSFORMER ON AVAILABLE POWER
A TO B	POWER OBTAINABLE ONLY WITH TRANSFORMER
B TO C	TRANSFORMER PERMITS INCREASED OUTPUT
ABOVE C	TRANSFORMER RESTRICTS OUTPUT TO HALF MAXIMUM

FIG. 11.36. *Curves relating power at particular voltages and a.c. generator speeds.*

FIG. 11.37. *Illustrating the compounding method of a.c. generator excitation.*



indicated by point *A* which is a point on the curve of available power at 100 volts against generator speed; for simplicity a 1 : 2 step-up ratio has been inferred. From the diagram it can be seen that the maximum available power with the transformer in the system is limited to half the maximum available power without the transformer, this limit being imposed by the current rating of the a.c. generator windings. Thus, to obtain the maximum power over the entire speed range it would be necessary to switch the transformer out of circuit or, by tap changing, to change the ratio from 1 : 2 to 1 : 1 at the speed indicated by point *C*. Transformer switching and tap changing has given difficulty owing to voltage surges but the principle, which is only applicable to variable-frequency a.c. generating systems, has been found to be a practical means of extending the effective speed range without adding very much weight, and this difficulty has been satisfactorily minimized.

Another method of obtaining more than one output voltage from an a.c. generator is the use of tapped or multiple stator windings. Tapped windings were used on some early "Britannia" systems but the practice was not continued because it was found advantageous to separate the outputs electrically and also because this could be done with little increase in weight. Electrical separation is necessary if two outputs are to supply three-phase bridge rectifiers and each rectifier is to have one of its output terminals earthed. This is because the a.c. generator star point assumes a potential with respect to earth which is approximately half that of the rectified output.

EXCITATION AND COMPOUNDING

It was explained under *Alternating-current Generators* in Chapter 6 that the excitation currents of many a.c. generators are high, rather higher than can be controlled by most of the proven types of carbon-pile regulators. An arrangement has therefore been devised for providing part of the excitation current independently of the regulator. The simplest arrangement

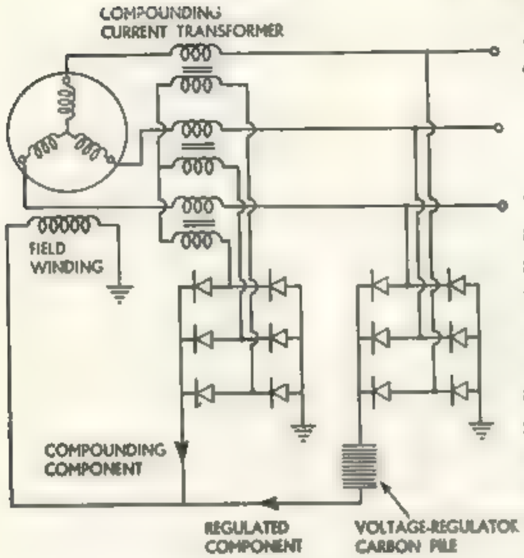


FIG. 11.38. *Simplified compounding circuit for the excitation of an a.c. generator in a rectified a.c. system.*

would have been to provide a constant excitation current a little lower in value than the minimum current ever required. Minimum current is required at maximum speed and minimum load and a suitable value for the constant part of the excitation current would be that indicated by *OA* in Fig. 11.37. However, it can be seen from the diagram that this is only a very small part of the maximum current required, which is indicated by *EF*, and would not relieve the carbon pile very much.

A more worthwhile arrangement, known as compounding, provides a component of the excitation current proportional to the a.c. generator load current. The ratio compounding current/load current is chosen so that, even at the highest speed, the compounding current is less than the excitation current required, the difference being provided by the regulator. It is convenient that, as explained in Chapter 6 (see *Load Characteristics*), changes of generator speed require only relatively small changes of excitation current when a generator is loaded. The ordinate *BCD* in Fig. 11.37 represents the excitation current required at half load and minimum speed. Of this, the part *CD* would be provided through the regulator and the part *BC* through the compounding circuit. The part *BC* would be unchanged by changes of generator speed or by small effects such as changes of generator air-gap arising from heating, but the generator regulator is sensitive to the generated voltage and would adjust the part *CD* accordingly. Should the design of the system allow the compounding current *BC* to exceed the total current required, *BD*, the system would be unstable and an abnormally high voltage would be generated.

Fig. 11.38 shows a simplified compounding circuit and Fig. 11.34 a compounding transformer with two sets of primary windings, one for each of the two system outputs. Small outputs, in systems having several outputs, such as the 28-volt output of the "Britannia 300" system shown in Fig. 11.39,

may not be passed through the compounding transformer, the additional excitation current required by the loading of this output being provided by the regulator.

It is a principle to be designed in to any system that each individual power source should be capable of independent operation. In rectified a.c. systems difficulty has sometimes been experienced in making the generators self-exciting, as explained in Chapter 6 (see *Excitation and Voltage Regulation*), and the system d.c. voltage has sometimes been used for initial excitation. Such an arrangement is deceptively satisfactory under normal conditions but is unsound because, if a fault occurs which simultaneously de-energizes the generators and disconnects or discharges the accumulator, it may be impossible to re-excite the generators after the fault has been removed.

REGULATION OF MULTIPLE OUTPUTS

It is perhaps worth remarking that the passing of an output through a compounding transformer does not achieve voltage regulation of that output. The sole function of compounding is to reduce the current loading of the regulator carbon pile. The system depicted in Fig. 11.34 has both outputs passed through the compounding transformer but only the d.c. output is

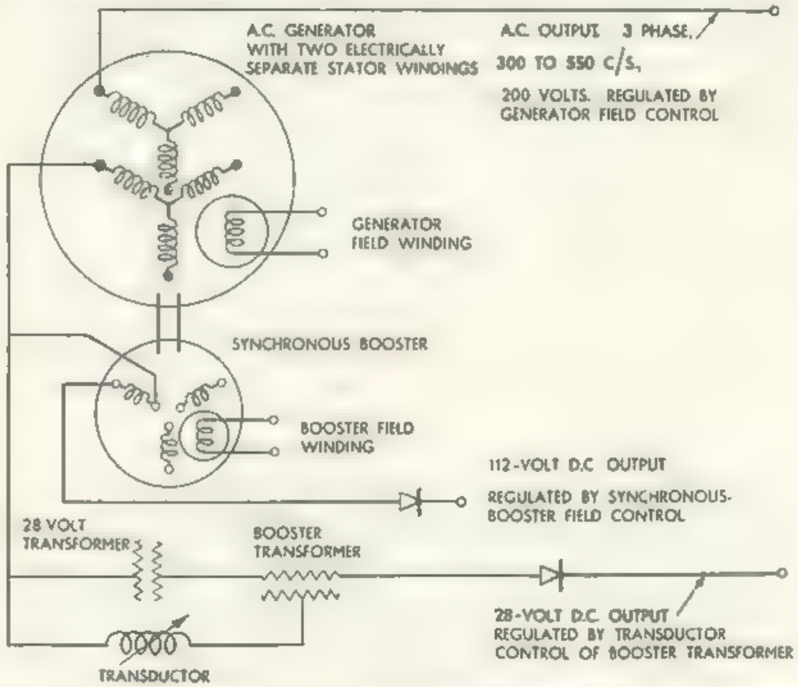


FIG. 11.39. *Simplified diagram of "Britannia 300" rectified a.c. generating channel.*

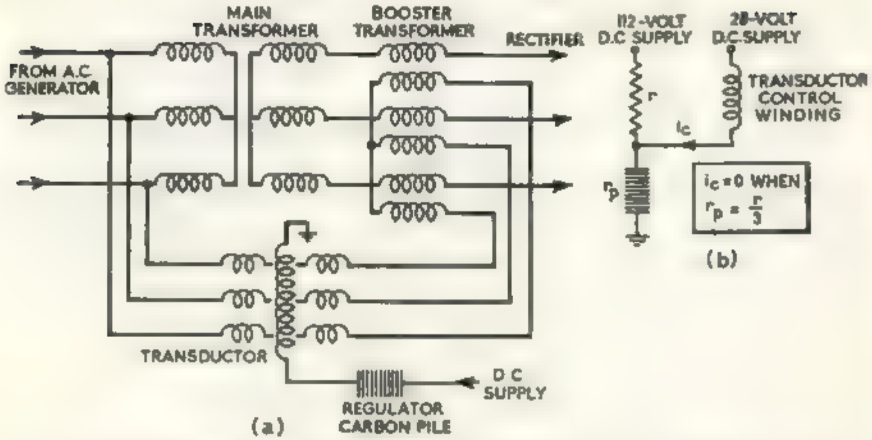


FIG. 11.40. (a) *Essential circuit of transductor-controlled booster transformer method of regulating a d.c. output.* (b) *A method of extending the working range of transductor control winding current.*

regulated. The voltage of this output is maintained constant regardless of the loading on either d.c. or a.c. outputs but the a.c. output voltage is affected by changes of d.c. loads. This is because the regulator adjusts the a.c. generator excitation to compensate for changes of volt-drops in the main transformer, rectifiers and other components in series with the lines feeding the rectifier. Alternating-current loading also causes volt-drops in the main transformer and in the a.c. lines, but for these volt-drops there is no regulating action except when they affect the d.c. output voltage. The regulation performance of the system of Fig. 11.34 may be summarized as follows.

D.C. Output: To voltage tolerances determined by the regulator.

A.C. Output: To a nominal voltage determined by the design of the system, and tolerances proportional to those of the d.c. output, +(A voltage proportional to the full-load volt-drop between the main transformer and d.c. output terminals)−(The full load volt-drop in the main transformer a.c. windings and a.c. lines).

This arrangement was accepted for a number of aircraft but closer regulation was desired and is being used in later systems.

Voltage regulation of three outputs is used in the "Britannia 300" system, shown in simplified form in Fig. 11.39. The a.c. output voltage is sensed by a carbon-pile regulator and the a.c. generator field current is controlled by this regulator to keep the voltage constant. If no other regulators were used the voltages of the two d.c. outputs would depend on a.c. loading. Separate regulation is obtained for the 28-volt output by a regulator which senses the output and controls the current in the control winding of the

transductor. This controls the output voltage of the series booster transformer which is added to the output of the 28-volt transformer. Regulation of the 112-volt output is achieved by a regulator which senses the output and controls the field current of the synchronous booster, the voltage of which is added to the output voltage of windings from the main a.c. generator. The synchronous booster is described in Chapter 6.

Details of the transductor-controlled booster transformer are given in Fig. 11.40 (*a*). The arrangement has been used on the Handley Page "Hermes" and "Victor", and on the "Britannias" and it is favoured mainly because it is free from moving parts. In each aircraft it forms part of the regulating systems of the 28-volt outputs which are rated at between 2 and 4 kW. per generator. An interesting point of design arises in connexion with the booster transformer. Ideally the voltages induced in its secondary windings should be in phase with the voltages of the corresponding secondary windings of the main transformer. If there were no phase shift between the primary line voltage, v_1 in Fig. 11.41, and the booster transformer secondary voltage, v_{b_2}, this ideal would be achieved, but in practice the transductor winding causes an appreciable phase shift. This may sometimes be partially corrected by a delta/star connected booster transformer instead of a star/star connected transformer as shown in Fig. 11.40 (*a*). Fig. 11.41 (*b*) is a phasor diagram indicating the conditions with these alternative connexions, and showing that the delta/star connexion gives better phasing.

An advantageous method of connecting the transductor control winding

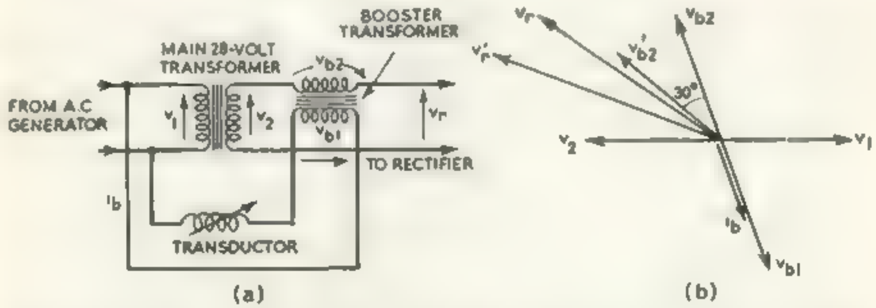


FIG. 11.41. (a) *Single-phase equivalent of the transductor-controlled booster transformer circuit shown in Fig.* 11.40(a). (b) *Phasor diagram for the circuit* (a) *showing how a delta/star connected booster transformer may be advantageous. Note:* (*1*) i_b *lags* v_1 *because the transductor is inductive;* (2) v_{b_1} *is in phase with* i_b *because the booster transformer load is mainly resistive;* (3) v_{b_2} *is anti-phase to* v_{b_1} *if the booster transformer is star/star connected and is 150 deg. lagging* v_{b_1} *if the booster transformer is delta/star connected. In the latter case the voltage is represented by* v'_{b_2}*;* (4) *rectifier voltage* v_r *or* v'_r *is the resultant of* v_2 *and* v_{b_2} *or* v'_{b_2} *and it can be seen that* v'_r *is greater than* v_r.

which can be used in systems having both high- and low-voltage d.c. outputs, is shown in Fig. 11.40 (*b*). With the simple circuit shown in Fig. 11.40 (*a*) the control winding current has a minimum value determined by the maximum resistance of the carbon pile, but the circuit of Fig. 11.40 (*b*) enables the current to be reduced to zero. The range of the booster transformer output is therefore increased with little or no increase in weight.

REGULATOR PECULIARITIES

Two effects, more than others, have troubled the designers of rectified a.c. systems. Firstly, voltage surges and, secondly, effects termed "cutting out". Voltage surges are liable to occur at switching on and at tap changing on the main transformer. They are particularly undesirable because rectifiers can be damaged by excessive voltage even when it is only applied for very short periods. To minimize the magnitude of voltage surges it is usual to ensure that the accumulator and the rectifier outputs are connected to the d.c. busbars before the a.c. generators are excited. As in d.c. systems, the accumulator accepts a large charging current if the system voltage tends to rise, thereby loading the generator and minimizing the voltage surge.

"Cutting out" implies that the a.c. generator is under-excited, or not excited at all, and is unable to deliver power. It has been caused by the armature of the carbon-pile regulator moving rapidly from its de-energized position and becoming fixed at the other extreme position, in which case the carbon pile is practically open-circuited. The armature may remain in this position because the voltage-sensing coil is energized. Two other possible reasons are magnetic "sticking" between the armature and pole face, and distortion of the spring such that it has no return force. These latter reasons have been known to apply to early regulators after full system voltage had been suddenly impressed on their voltage-sensing coils.

A small but significant difference between some rectified a.c. systems and d.c. systems is that the regulator voltage-sensing coils are connected to the d.c. busbars and may be energized suddenly, and at full voltage, before the generators are run up to speed or excited. Even if this does not cause the armature to overshoot and "stick" the armature assumes a near normal operating position before the generator is operating. It has been suggested that, under these conditions, the regulator is much more prone to "cutting out" if the generator voltage overshoots before settling to its normal value.

Another cutting-out effect which is likely to occur when starting the system is that the position taken up by the regulator armature does not permit the generator voltage to rise high enough to overcome the rectifier forward volt-drop and deliver power to the system. This is most likely to occur if the system voltage is high and if the system is lightly loaded, and it has been prevented by the use of "anti-cutting out" circuits. These restrict

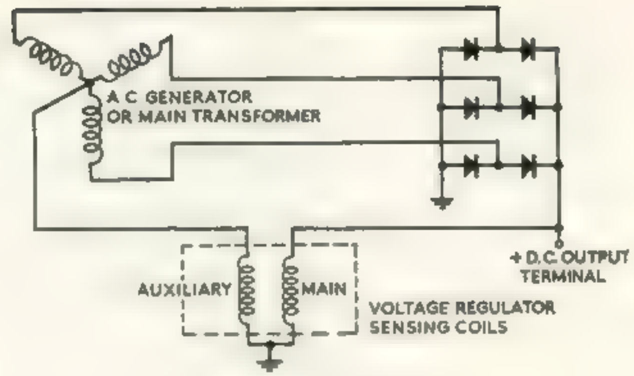


FIG. 11.42. *Voltage regulator with anti-cutting-out auxiliary coil.*

the m.m.f. available to move the regulator armature, to a subnormal value, until the a.c. generator is fully excited and delivering power. Thus the armature is nearer its de-energized position, the pile is compressed to give low resistance, and the generator is assured of adequate excitation current to enable it to deliver power. Once delivering power, provided the system is not too lightly loaded, stability is assured by the load-sharing circuit which is described later (see *Load Sharing*). Fig. 11.42 shows a type of "anti-cutting-out" circuit employing an auxiliary voltage-sensing coil on the regulator. This is supplied from the star point of the a.c. generator, or of the transformer secondary winding if a main transformer is used. The main voltage-sensing coil is energized by the system voltage but supplies only a part of the m.m.f. required to move the regulator armature into a position corresponding to that voltage. The remaining m.m.f. is supplied by the auxiliary coil which does not become energized until the rectifier begins to deliver current. This is because the star point is isolated until the rectifier becomes conducting, after which it assumes a potential of about half the rectified voltage. This is explained in Chapter 8 (see *Star Point Potential*). Other "anti-cutting-out" circuits also make use of the potential of the star point but, by simple resistance networks, avoid the need for an auxiliary coil.

One British aircraft system with a notably different regulator arrangement was that of the early "Comets". This employed a.c. generators which required a relatively small maximum excitation current of 28 amp., and which was controlled entirely by a single carbon-pile regulator. It was found necessary, however, to extend the range of the pile resistance variation at the lower end and this was achieved, as shown in Fig. 11.43, by arranging a pilot regulator to shunt some of the current from the voltage-sensing coil of the main regulator. In this way the rate of change of the main regulator voltage-sensing coil m.m.f. is made greater than the rate of change of system voltage. Some increase in regulator sensitivity is also obtained. This system has been

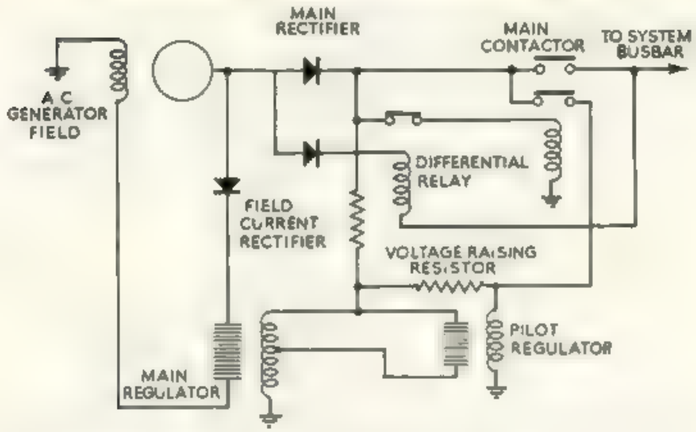


FIG. 11.43. *Simplified diagram showing the voltage-regulation system employed on the de Havilland "Comet 4".*

retained on the Comet 4. Initial excitation is assured by a small permanent magnet built into the rotor of the generator.

In the early system, voltage surges at starting were intended to be avoided by running up the engines with the a.c. generators excited, thus ensuring a relatively low rate of rise of voltage. An alternative arrangement, necessary to enable a generator to be reconnected to the system with its engine running, was a manually operated resistor in the generator field circuit. This was used to increase the generator voltage gradually to a value at which the generator delivered power. Starting the engines with the generators excited required some increase of starting power.

Operation of the Comet 4 system is simplified by automatic connexion of the generators to the system as soon as their voltages are sufficiently high to enable them to deliver power. This is achieved in the same way as with some d.c. systems described earlier (see under *Reverse-current Cut-outs*), by using a differential relay which compares generator voltage with the system voltage and closes a contactor when the former is about half a volt higher than the latter. A simplified circuit of this arrangement is shown in Fig. 11.43. When the generator is shut down the differential relay opens and disconnects the generating channel from the system. The relay is held closed during normal operation by the volt drop across the main rectifier and contactor contacts.

LOAD SHARING

Load sharing is necessary between the d.c. outputs of rectified a.c. generating channels but not between the a.c. outputs because these are never

paralleled. Only real load sharing and not reactive load sharing is therefore necessary. The method generally used, which ensures stability and good load sharing, is identical in principle with the equalizing-coil constant-voltage method used in d.c. systems (see *Regulator Equalizing Coil*). The Comet 1 and some U.S.A. systems used equalizing resistors in series with the rectifier outputs, but most British systems, including the Comet 4, derive the equalizing voltage from three-phase current transformers in the a.c. lines followed by three-phase bridge rectifiers. The advantages of this are:

1. Lower power losses. Values of 15 and 125 watts per generator have been quoted for current transformers and series resistors respectively.
2. The transformers may be designed to give optimum voltage for the equalizing circuit. Voltages of between 10 and 30 have been used, whereas no more than two volts can be derived from series resistors.
3. The equalizing circuit may be electrically isolated and thereby rendered immune to a single fault to earth or live conductor.

As in d.c. systems it is necessary to disconnect the equalizing circuit of any non-operating generator and provision is made in most systems for automatic disconnexion by a relay which is normally energized by the line voltages. This is the load-sharing isolator shown in Fig. 11.34. It can also be used for other protective functions.

In some multiple output systems equalizing voltages have been obtained from points in the system which are at potentials related to the volt-drops across series components in the a.c. lines. An example of this can be found in

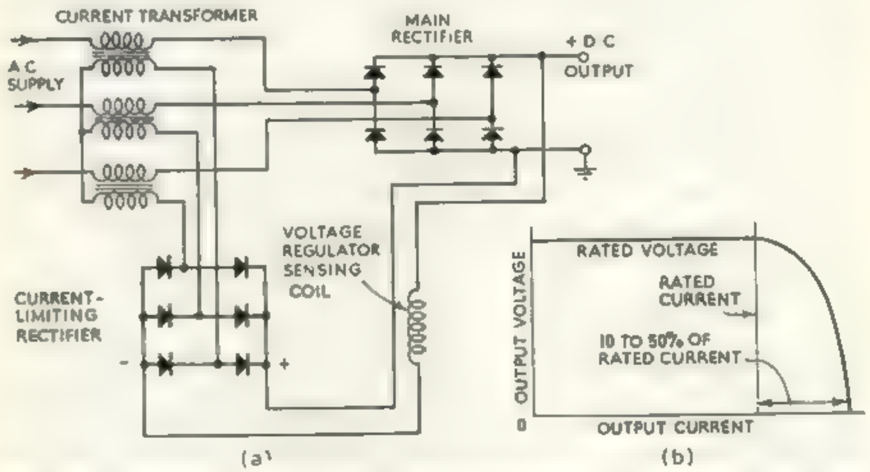


FIG. 11.44. *Protective arrangements associated with the a.c. generator and transformer-rectifier unit.* (a) *Current-limiting circuit.* (b) *Output characteristic for a T.R. unit with current-limiting circuit.*

the "Hermes" system (Ref. 19). Although eliminating the load-sharing transformer and rectifier, this arrangement has the disadvantage of depending for its accuracy on the impedances of several components which are designed primarily for other functions.

PROTECTIVE CIRCUITS

The following Sections discuss the protective arrangements associated with the a.c. generator and T-R unit. Arrangements on the load side of the d.c. busbars are similar to those of d.c. systems discussed in Chapter 10 (see *Protective Methods*). The need for special rectifier protective arrangements has been questioned and it is probable that future systems will be simplified in this respect.

Current Limiting. The precaution of restricting the maximum forward current is taken because rectifiers are liable to be damaged by heating even during overloads of short duration. At the time when this was first used in rectified a.c. systems, a method of forward current limiting, described in Chapter 5 (see *Voltage Regulator, Carbon-pile Type*), was in fairly general use in d.c. systems and the two schemes have similar characteristics. A current-limiting circuit and a graph relating output voltage and current are shown in Fig. 11.44.

The operation of the circuit is as follows. Normal current through the voltage-regulator sensing coil is passed through the current-limiting rectifier in the forward direction. This biases the rectifiers to low-resistance values (see Chapter 8, *Forward and Reverse Resistances*), which practically short-circuit the current transformer. The normal current from the current transformer, which is determined by the transformer turns ratio, is less than the biasing current. Abnormal forward current from the generator causes the transformer current to exceed the biasing current, and when this occurs the current-limiting rectifier begins to function. It develops a voltage, as indicated in Fig. 11.44 (*a*), which assists the busbar voltage and increases the current through the regulator sensing coil. The regulator interprets the increased current as an abnormal system voltage and reduces the generator excitation.

SHORT-CIRCUIT BETWEEN A.C. LINES

A circuit which is sensitive to short-circuits and which is used to operate a relay to de-energize the generator is shown in Fig. 11.45 (*a*). It has a three-phase transformer with a zigzag star or interconnected star secondary winding and this is used to feed three separate single-phase bridge rectifiers. The output voltages of these rectifiers are compared by two relays and differences of their outputs energize one or both relays. Operation of either relay causes a time-delayed relay to begin to operate and at the end of the delay period this relay causes the generator to be de-energized. The circuit is sensitive to changes in

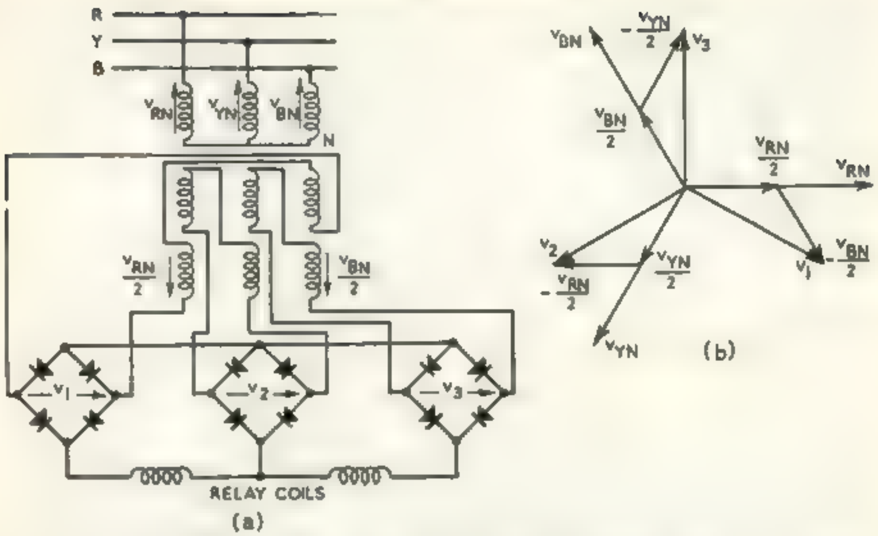


FIG. 11.45. (a) *Alternating-current line short-circuit protection circuit.* (b) *Phasor diagram for the circuit shown in* (a).

the phase relationship as well as relative magnitudes of the phase voltages. This may be confirmed by redrawing the phasor diagram of Fig. 11.45 (*b*) with unequal or displaced voltages and comparing the magnitudes of the rectifier voltages, v_1, v_2 and v_3. Mean rectifier outputs are proportional to the magnitudes of these voltages and the relays are sensitive to their differences.

The circuit is sensitive to faults, not only on the a.c. lines to which it is connected, but also to faults on a.c. lines to which it is connected through transformers. As an example, in the generating channel shown in Fig. 11.34 the short-circuit protection could be expected to cover the lines between the the generator and the main transformer, and between the transformer and the a.c. loads, in addition to the lines to which it is connected. Faults beyond the a.c. output terminals should be cleared by disconnecting the faulty load circuit from the system and the time delay, previously mentioned, should allow this to occur. The circuit would not respond to the possible, but unlikely, case of a perfectly symmetrical three-phase fault, but power failure would almost certainly be detected by the load-sharing isolator circuit, mentioned in the Section *Load Sharing*.

An alternative method of a.c. line protection which has not been generally used but shows signs of gaining favour, is differential current protection, as described in Chapter 10 (see under *Generator to Busbar*). This is unaffected by faults beyond the current transformers or by asymmetrical three-phase loading and consequently requires no co-ordinating time delay.

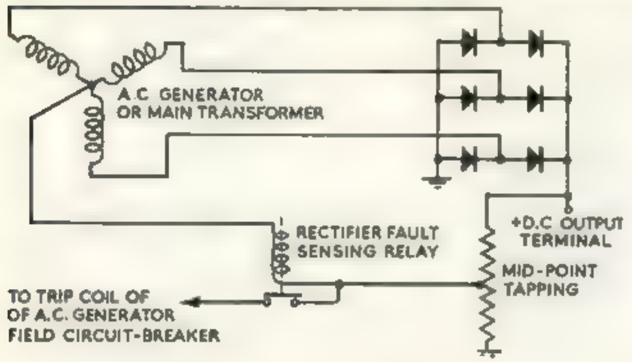


FIG. 11.46. *Rectifier fault-protection circuit.*

RECTIFIER FAULT PROTECTION

Rectifier failures can be detected by sensing the potential difference between the star point of the main transformer or a.c. generator, whichever is connected directly to the rectifier, and one of the rectifier output terminals. It is shown in Chapter 8 (see *Star Point Potential*) that the potential of the star point has a mean value equal to about half the rectifier output. Thus a relay connected as shown in Fig. 11.46 is normally de-energized. In the event of a breakdown of one or more arms of the three-phase bridge rectifier the relay becomes energized and can be arranged to de-energize the generator. It is necessary to prevent the rectifier fault protection relay from operating during the initial excitation of the generator, and this is achieved by using a thermal delay or by disconnecting the circuit until excitation is normal. The load-sharing isolator can conveniently perform the latter function.

Some rectifier breakdowns will result in a flow of reverse current from the d.c. busbar and this would not be checked by de-energizing the generator. A reverse-current circuit-breaker is therefore required as shown in Fig 11.34, and, as an additional precaution, this may also be arranged to de-energize the generator.

OVER-VOLTAGE AND UNDER-VOLTAGE PROTECTION

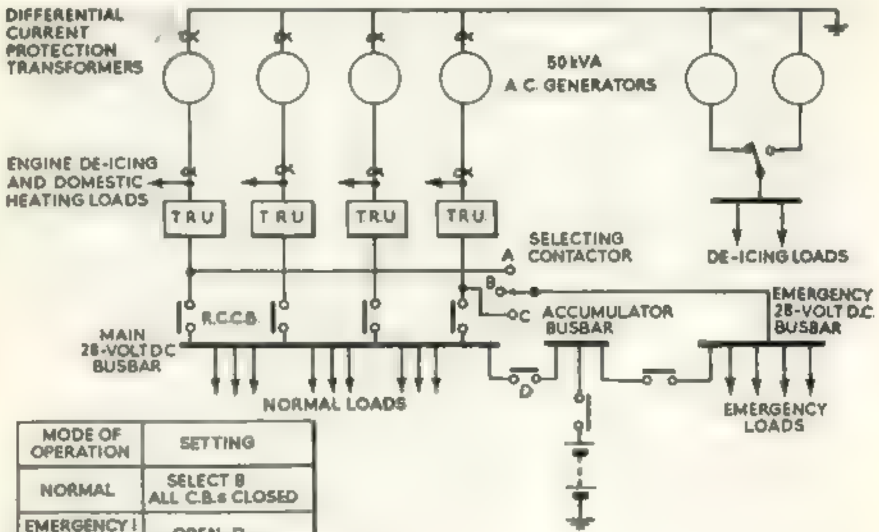
Since the d.c. outputs of rectified a.c. systems are always paralleled, over- and under-voltage protection is closely associated with the load-sharing circuit as described in Chapter 10 (see *Generator to Busbar*). In this case, however, reverse current cannot flow and the only action required of the under-voltage relays is the opening of the load-sharing circuit of the faulty channel. The over-voltage relay is required to de-energize the faulty channel in addition to opening the load-sharing circuit and this can be done by tripping the R.C.C.B.

Emergency Supplies. As in d.c. systems the accumulator is available for

d.c. loads. The main a.c. loads of rectified a.c. systems are generally not absolutely essential to flight and often no provision is made to power them in emergencies involving the loss of all generators or their drives. Individual generator failures are often covered by the provision of load transfer switching. On the Handley Page "Victor" provision was made for generating power and rectifying at 112 volts, in the event of losing all the generator drives, by windmilling the engines. As windmilling speeds were expected to be much lower than normal engine speeds, a contactor was provided to enable the 112-volt rectifiers to be supplied from the 200-volt windings of the a.c. generators.

One British operator, on introducing the "Hermes" having a rectified a.c. system, fitted an auxiliary 28-volt d.c. generator driven from one of the main engines. Subsequent experience with the system indicated that this precaution was unnecessary.

Earthing. The same practice is followed as for d.c. systems and the negative terminals of all the main rectifiers are earthed. From the explanation given in Chapter 8 (see *Star Point Potential*) it follows that it is impossible also to earth the neutrals of the a.c. parts of the system, excepting those parts, if any, which are isolated by transformers from the rectifiers.



MODE OF OPERATION	SETTING
NORMAL	SELECT B ALL C.B.s CLOSED
EMERGENCY 1 (BUSBAR FAULT)	OPEN D SELECT A OR C
EMERGENCY 2 (ALL GENERATORS FAILED)	D OPEN SELECT B

FIG. 11.47. *The layout of a rectified a.c. system for a four-engined aircraft; it has an emergency busbar.*

A LARGE RECTIFIED ALTERNATING-CURRENT SYSTEM

A layout for a system for a four-engined aircraft is shown in Fig. 11.47. It is similar to that being installed in the early Vickers "Vanguards" and shows a trend towards simplification without unduly curtailing the flexibility necessary to allow operation with faults on the system. One major simplification is the omission of a 112-volt d.c. supply. From the discussion on d.c. system voltages (see *Choice of Voltage*), it will be appreciated that this may be omitted without incurring a weight penalty if the d.c. power is small. In the case of the "Vanguard", each of four generating channels can deliver 14 kW and the justification probably rests on the greater availability of 28-volt components and ground equipment, and the experience of operators' servicing staffs.

LAYOUT AND EMERGENCY SUPPLIES

Generators 1 to 4, rated at 50 kVA, each supply variable-frequency a.c. power for the de-icing of the power plant with which they are associated and for a part of the domestic heating load. Since these generators are driven directly from the engines they cannot be operated in parallel and if an alternative source of supply is required for any of these loads, transfer switching must be installed.

These four generators also supply T-R units having regulated 28-volt outputs which are paralleled by connexion to the main 28-volt busbar and employ load-sharing circuits such as that described earlier (see *Load Sharing*). All loads are supplied from the single main busbar. In the event of this becoming short-circuited it can be isolated by operation of the generating channel circuit-breakers and the accumulator circuit-breaker. Essential loads are provided with an alternative source of supply from the emergency d.c. busbar which itself can be supplied from one or both of two generating channels, Nos. 1 and 4, and from the accumulator. In the event of the failure of all generators, or a simultaneous main busbar fault and failure of generators 1 and 4, the essential loads can be supplied for a limited period from the accumulator alone.

It should be noted that unless comprehensive transfer switching is used, the variable-frequency a.c. power supplies obtained from each of the four generators, taken individually, are inherently less reliable than the d.c. supply. Power available from the latter source is adequate, even in the event of up to two generating channel failures, for all the most necessary normal loads. Only under extreme circumstances does the supply become severely restricted.

The accumulator, as in a d.c. system, is normally connected to the main busbar. It is not required to supply power, except for engine starting and when the main engines are not operating, but serves to minimize ripple on

the supply and provides additional capacity which is useful for the operation of some protective devices.

Generators 5 and 6 virtually form an independent variable-frequency a.c. system. They are driven from different main engines and each serves as a stand-by for the other in the event of a generator or drive failure. In the "Vanguard", this system supplies power for tail-unit and windscreen de-icing installations, a total load of about 40 kW.

Requirements for constant-frequency a.c. power are met, as in d.c. systems, by the installation of d.c. to a.c. convertors. In the "Vanguard" three 3kVA convertors are installed, two of which are normally used, the third serving as a stand-by. A small convertor of 400 volt-ampere output is supplied from the emergency busbar to power emergency radio and instrument loads.

PROTECTION

The main a.c. feeders from generators to de-icing and T-R unit contactors can be protected by the circuit described in the Section *Short-circuit between a.c. Lines*, or by differential current protection (see Chapter 10, *Generator to Busbar*). In a civil aircraft, owing to the fact that it is convenient to locate the T-R units together for easy servicing and to utilize a common cooling air supply, the a.c. feeders are likely to extend from the generators to a central region and the dispersed load busbars, such as are shown in Fig. 11.30, are unlikely to be used. This has not been true of all rectified a.c. installations; the "Ambassador", for example, had T-R units located in each of the main wheel recesses.

With centrally located T-R units and a single load busbar, as shown in Fig. 11.47, the lengths of d.c. feeder from the T-R units to the busbar are likely to be short. These can be protected by any of the methods discussed in Chapter 10 (see *Generator to Busbar*) but are most likely to be fitted with a reverse-current circuit-breaker at the busbar end.

CHAPTER 12

Ancillary Equipment and Systems

In Chapter 2 an attempt was made to define and discuss reliability, and it was stated that perfect reliability is unattainable. Because of this, if for no other reason, accidents will happen, and when they occur two things, primarily, demand attention. These are, safety and economy. The safety of passengers and crew is a consideration of the highest importance, but also is the safety of other aircraft, of those over whose heads aircraft fly, and the safety of ground crews. Economy requires that in the event of an accident, the minimum interference is caused to normal operation and the minimum damage is sustained by the aircraft. Economy, as well as safety, is a necessary consideration, because civil flights must, generally, be economical or be withdrawn. Likewise, military operation must be as inexpensive as possible or it cannot be sustained at the desired level.

EMERGENCY LANDINGS

In civil aircraft, passengers must remain in the aircraft until it is grounded or ditched, since they have no alternative safe means of descent, but immediately after landing their safety usually lies in a speedy exit from the aircraft. Much can be done to facilitate their exit but the most important thing, generally, is to prevent or delay the outbreak or spread of fire. The electrical aspects of this task include: (1) operation of fire extinguishers; (2) closing of fuel cocks; (3) switching on of emergency lights; (4) isolation of accumulator supply from all other parts of the system, and when ditching; (5) inflation and launching of dinghies; (6) release of marker buoys. The automatic

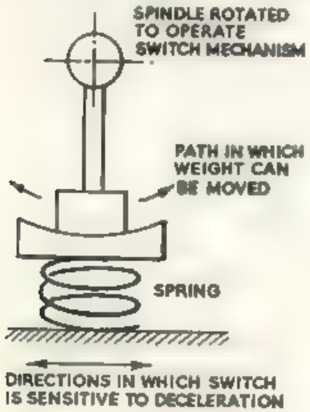
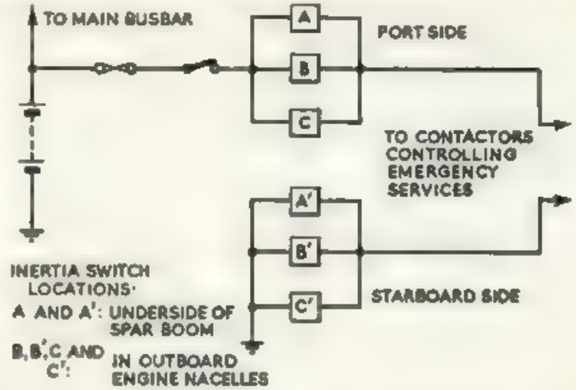


FIG. 12.1. *The princpile of an inertia switch.*

FIG. 12.2. *Position and connexion of inertia switches.*



initiation of these operations is effected by various types of switches, of which the following three are in general use.

Inertia Switches. Fig. 12.1 illustrates the principle of one type of inertia switch. Adjustment of the spring tension determines the deceleration at which the weight is moved and the switch mechanism operated. Typical values lie between 2 and 4*g*. and the mechanism is usually non-resetting. Several of these switches are installed in an aircraft, a typical layout being shown in Fig. 12.2. It can be seen that at least two switches must be operated before the emergency services are effected. This is one of the precautions taken to avoid the inadvertent operation of the emergency services which, since they include the shutting down of all engines, would be very dangerous.

Contact Switches. These are switches which are operated by contact with other bodies, usually the ground. They are often arranged to form a strip and are installed on surfaces which are likely to make contact in the event of an emergency landing. Unlike high deceleration, contact is likely to occur during servicing and handling, and these switches are usually only closed while contact pressure is applied. As with inertia switches, it is desirable to make the emergency services dependent on the operation of at least two switches. To cover the probability that contacts during a crash landing will occur only momentarily and not simultaneously at all switches, a control unit is required which records momentary contacts and operates the emergency services when two contacts occur at different switches in quick succession.

Immersion Switches. These depend on the conductivity of sea water and consist of two sets of electrodes, of a few square inches surface area, positioned fairly close together. The electrodes are permanently energized from a d.c. supply, and immersion in sea water can cause a flow of current sufficient to operate a sensitive relay which in turn operates the emergency services.

Power for emergency services is generally obtained from the main power system accumulators. To ensure that this source is available after ditching

it is necessary to install the accumulators in a position where they will not be flooded.

Crew Escape Hatches. In military aircraft, economy requires the safe landing of an aircraft whenever possible but when this is impossible safe escape of the crew is always required. Special escape arrangements are generally unnecessary for low-speed aircraft, but escape from high-speed aircraft often requires the use of ejector seats to propel the crew members safely clear of the aircraft. Before the seats can be ejected it is usually necessary to shed the canopy or part of the cockpit roof and this is often done by using explosive bolts which are fired electrically. The power for such firing circuits is almost invariably derived from an accumulator which is separate from the main power system, in order to ensure that the supply will be available regardless of the condition of the aircraft as a whole.

Safety of Other Aircraft. The danger of collision, and confusion or delay which may lead to dangerous situations is greatest at night, but is increasing in importance at all times as aircraft speeds and traffic movements increase. At night navigation lights and beacons are required, as described in Chapter 9. Communication with traffic controllers is important and may occasionally be vital. The accurate functioning of instruments which assist the navigator to follow a prescribed course at a particular altitude may also contribute to the safety of other aircraft. In the future it is likely that a form of collision warning radar may become general.

Safety of Ground Crews. This requires attention to detail design to minimize the risk of accidents such as can occur with any large machine. Accidents of an electrical nature are likely to occur because much of the aircraft equipment can be energized from the accumulators. This allows the possibility of accidental short-circuits with the attendant fire and explosion risks, and the unintended operation of electrically driven mechanisms such as flaps and doors. Methods of minimizing the risk of unintentional operation are discussed in Chapter 10 (see *False Operation*, page 239).

FIRE DETECTORS

Flame Switches. These are temperature-sensitive relays, using the bimetal or differential expansion principle, which are installed in positions where fire is most likely to occur. Operating temperatures are between about 150 and 500 deg. C. Often several switches, located in one region, are connected in parallel to operate a warning lamp, and operation of the appropriate extinguishers is carried out by the crew. The switches are usually of a resetting type.

Wire Detectors. These consist of uninsulated metal tubing packed with a salt and having a bare metal coaxial centre conductor. The tube is normally

at earth potential and the centre conductor is energized from an a.c. supply. The salt filling serves as an insulator at normal temperatures and becomes conducting at higher temperatures. The temperature at which conductivity becomes significant depends on the nature and mixture of the filling and usually lies between 100 and 400 deg. C. Conductivity is sensed by a control unit, which may be principally a magnetic amplifier, and when this reaches a predetermined high level the control unit operates a warning indicator. A typical magnetic amplifier control unit has a peak power consumption of 10 watts and weighs 0·7 lb.

The advantages of the wire type of detector are several. The wire is light and flexible and can therefore be installed liberally and easily. Weights of less than 0·15 ounces per foot and bends to a minimum radius of one inch are typical. A total length of up to 100 feet can be used in conjunction with one control unit, although installations of such length are not usual, and overheating of less than one-foot length is sufficient to operate the warning indicator. The wire may be joined, and lengths having different operating temperatures may be connected in series without the need for co-ordination. Both ends of a detector circuit are generally connected to the same control unit so that operation is unaffected if the wire is broken. The changing conductivity of the filling with temperature, although not linear, can be used to give a continuous indication of temperature.

The likelihood of false operation of the wire detector is minimized by choosing a filling which has the lowest possible operating resistance, usually less than 100 ohms, and a normal resistance at least 30 times greater. Leakage resistance, arising from such things as moisture at plug and socket connectors, is not likely to approach a value comparable with the wire operating resistance.

Fire Extinguishers. A commonly used type of extinguisher consists of a metal bottle containing methyl bromide under pressure. These are available for manual operation and also with pressure-release devices so that discharge occurs if the internal pressure is raised by excessive ambient temperature. The most extensively used method of discharge is by electrically firing a cartridge. This enables extinguishers to be connected for remote operation by the crew and also for automatic firing in the event of emergency landings, as described under *Emergency Landings*. A 28-volt d.c. supply is generally used for firing.

ELECTRICAL DE-ICING

This practice, which was mentioned in Chapter 9, has been the subject of considerable development although basically it is simple and there are no fundamental differences between the various systems and installations.

Heater Mats for De-icing. These are resistance elements, embedded in or fixed to an insulating base. One type of mat which is being installed on several

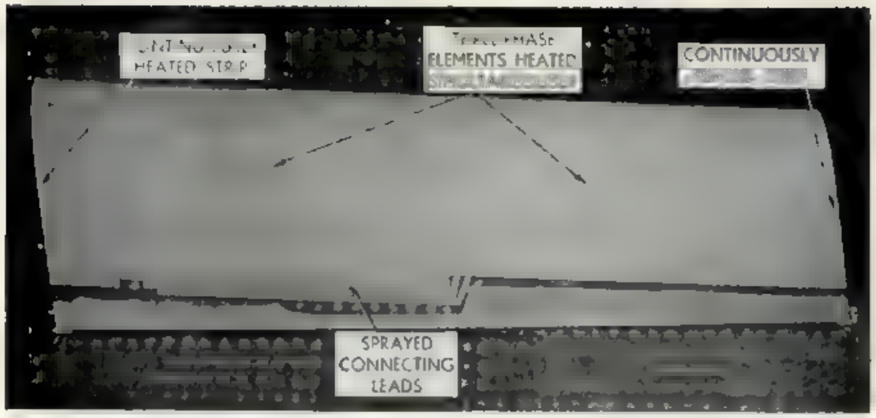


FIG. 12.3. *Heater elements applied to a leading-edge section of the Vickers "Vanguard" tail-plane.*

new British aircraft consists of a layer of thermo-setting insulating resin reinforced, in some cases, with glass cloth on which is formed a pattern of heating elements. The natural adhesion of the resin permanently bonds the mat to the aircraft surface. The elements are covered with an insulating layer similar to the base. The resin is applied either by brush or spray and the elements are produced by flame-spraying either Kumanal, which is a copper-manganese alloy, or aluminium. A little more than 90 per cent of the surface can be covered with heater element. Fig. 12.3 shows an element applied to the leading-edge section of the Vickers "Vanguard" tail-plane (see also Fig. 12.4).

Such a mat can be designed to dissipate between 0·1 and 50 watts per sq. in. and to operate safely at 150 deg. C., although normal operating temperatures rarely exceed 80 deg. C. Owing to its low thermal capacity and distributed heater element, a very rapid temperature rise is possible. This can be as high as 5 Centigrade degrees per second for mats dissipating about

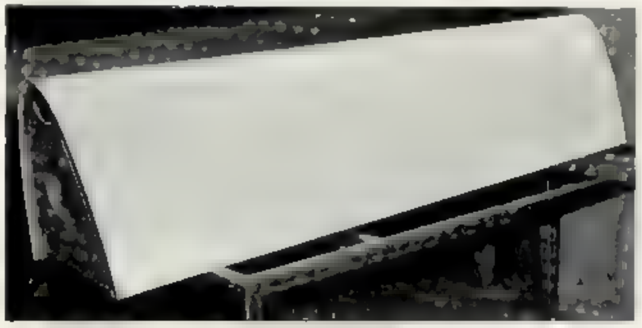


FIG. 12.4 *The finished form of the heater mat shown in Fig.* 12.3.

20 watts per sq. in. Mats of this type weigh between 0·3 and 0·85 lb. per sq. ft. and are between 0·03 and 0·07 in. thick. Pre-fabrication, instead of direct forming on the aircraft surface, is possible if glass cloth is used to reinforce the insulating resin.

Temperature Control. This may be required to prevent the occurrence of excessive mat temperatures, since the heating intensities required at some mats under icing conditions are such as to cause overheating under other conditions of flight or during ground running. Surface temperature control may also be required as a means of avoiding or minimizing an effect called "run-back". This is the melting of ice which runs to unheated areas and freezes again.

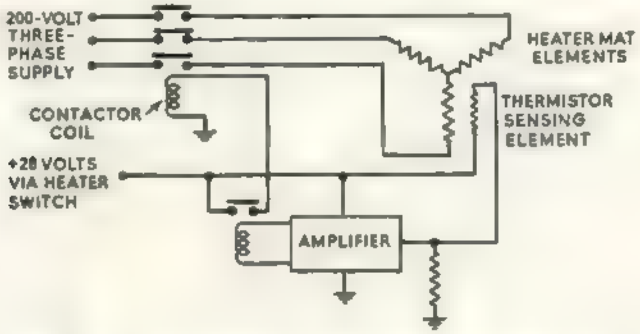


FIG. 12.5. *The temperature control system of a heater mat.*

Temperature control may be secured by an arrangement such as that indicated in Fig. 12.5, where the sensing element is a thermistor, the resistance of which decreases rapidly with increasing temperature. Alternative arrangements which avoid the need for a separate sensing element, use heater mat elements having different temperature coefficients. These elements can be connected to form the arms of a bridge or three-phase star circuits, and the unbalancing of the bridge or changing of the star-point potential respectively, can provide a control signal. After amplification this signal can control the heater power supply as shown in Fig. 12.5.

Mat Disposition and Heating: Static Surfaces. Ice forms mainly on the forward-facing surfaces. These surfaces are divided into areas for intermittent heating and these areas are separated by continuously heated strips. Fig. 12.6 shows a typical arrangement. The design objectives are to prevent the formation of ice on the strips and to shed it rather than melt it from the intermittently heated areas. Melting is minimized to avoid "run-back". The continuously heated strips are principally along the leading edges of the tail-plane and fins, and chord-wise at intervals along these surfaces. The leading-edge strips are necessary to prevent the formation of a cap of ice

which might not be shed by the successive heating of corresponding areas on the upper and lower surfaces. Chord-wise strips between intermittently heated areas are necessary to cause shedding because adjacent areas are not simultaneously heated.

Intermittent heating is usually achieved with a motor-driven distributor switch. Ideally, the durations of both the "on" and the "off" periods of the intermittently heated areas should be variable to suit different icing conditions. The length of the "on" period should be just sufficient to shed the ice because excessive heating melts ice on adjacent areas and causes "run-back". The "off" period should not be long enough to allow excessive ice build-up

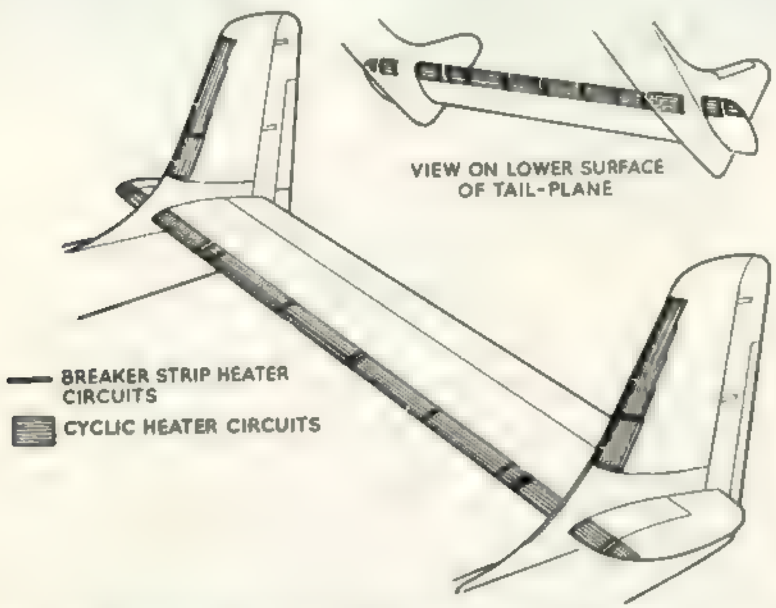


FIG. 12.6. *Mat disposition and heating on static surfaces. An example showing the general arrangement of the de-icing heaters on the tail plane of an Armstrong Whitworth "Argosy".*

but should not be so short that there is insufficient ice to shed. A thin ice film tends to melt instead of shedding. The individual adjustment of these periods is not easily accomplished and is not provided except in particularly critical applications such as helicopter rotors. As a compromise the speed of the distributor switch is sometimes made adjustable in two or three steps. A typical installation has ten intermittently heated areas and heats each successively for 15 or 30 seconds. Thus a complete de-icing cycle takes either 150 or 300 seconds.

Moving Surfaces. When de-icing propellers it is necessary to de-ice all blades simultaneously since asymmetrical shedding of ice leaves the propeller unbalanced and causes vibration. Intermittent heating is usual but the "off" period must be limited to avoid excessive ice build-up which would seriously increase the blade drag or which would self-shed and cause unbalance. Heater mats are usually fitted to the spinners and to the leading edges of each blade but extend only for about the first third or half of the radius. From this point to the tip, kinetic heating of the blade often prevents ice formation, and high centrifugal forces assist self-shedding in relatively small particles.

The power required for a complete propeller varies with propeller size and usually lies between 6 and 15 kW. Heat is applied for periods of between 15 and 100 seconds with "off" periods of from 30 to 300 seconds. As with static surfaces, control of these periods is sometimes required. Power is fed into the propeller by slip-rings; radio interference arising from these must be suppressed. It is not usual to subdivide the propeller heater mats for successive heating, even of symmetrically located areas, because this necessitates the use of extra slip rings or a distributor in the spinner. Helicopter rotors are subdivided because the power required to de-ice all parts of a complete rotor simultaneously is impracticably high. They require mats on the leading edges from about one-third of the radius out to the tips. To minimize the number of slip-rings a distributor is necessary in the rotor hub.

Mechanical Protection. Protection is sometimes required, mainly at the leading edges, against hail, and against stones thrown up from the runway at take-off. One method of achieving this is to apply a covering layer of resin loaded with metal particles. This layer may be 0·010 to 0·015 in. thick and weigh between 0·2 and 0·3 lb. per sq. ft. This kind of protection is adequate for surfaces subject to speeds up to about 500 m.p.h. but at higher speeds, such as are experienced near the tips of helicopter rotor blades, a thin metal sheath may be necessary. Mats near the roots of helicopter blades are subjected to considerable flexure but this does not seem to cause trouble. The resin-laminate type of heater mat generally has a smooth finish and, as may be seen from Fig. 12.4, its presence is barely discernible after the normal surface finish has been applied.

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